Introduction

$e_d = B l_e v \sin\theta$

$e_d = (\bar{v} \times \bar{B}) l_e \sin\theta$ Fleming's Right Hand Rule

$= (\bar{B} \times \bar{v}) l_e \sin\theta$ Flemings Left Hand Rule

Flux Linkages(ψ) $= N\phi$

$e_s = \frac{d(\psi)}{dt}$;

If one quantity opposses another quantity $\phi = -180^\circ$

If One quantity opposes changes in another quantity $\phi = -90^\circ$

$e_{self} = -N_1 \frac{d(N_1\phi)}{dt} = -N_1 \frac{d\phi}{dt} = -N_1 \frac{d\phi}{di}\frac{di}{dt}$

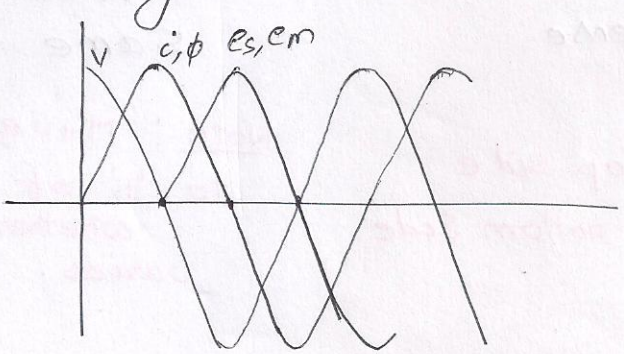
$e_{self} = -L_{self} \frac{di}{dt}$; $\boxed{L_{self} = N_1 \frac{d\phi}{di}}$

$e_{mutual} = -\frac{d(N_2\phi)}{dt} = -N_2 \frac{d\phi}{dt} = -N_2 \frac{d\phi}{di}\frac{di}{dt}$

$\boxed{e_{mutual} = -M \frac{di}{dt}}$ $\quad M = N_2 \frac{d\phi}{dt}$

When current in coil A changes, flux linkages in coil A changes $\Rightarrow$ Self Inductance

When current in coil A changes, flux linkages in coil B changes $\Rightarrow$ Mutual Inductance.



v, e_s – 180° phaseshift

v, e_m – 180° Phase Shift

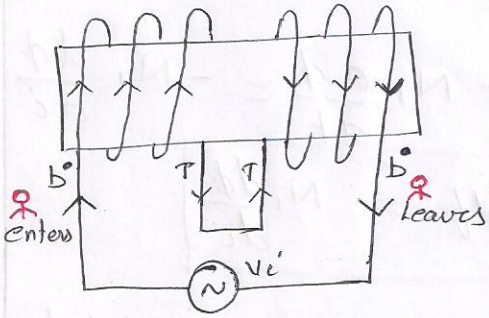
Dot Convention

Begin & Termination are to be decided by sense of winding not by direction of currents

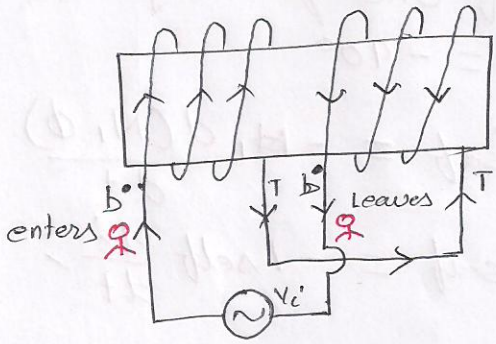
Pot Dot marks either at begin or terminal end of both coils

If current enters the dot in both coils M +ve

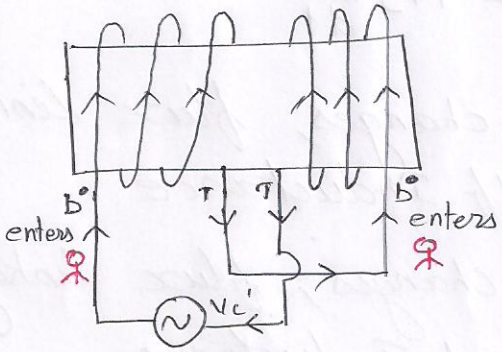
If current enter dot in one coil & leaves the dot in another coil M -ve.



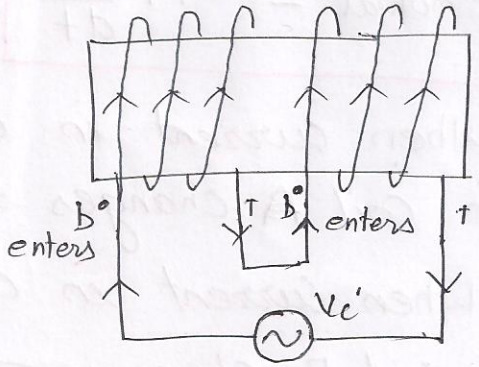
M -ve
Different Sense



M -ve
Same sense



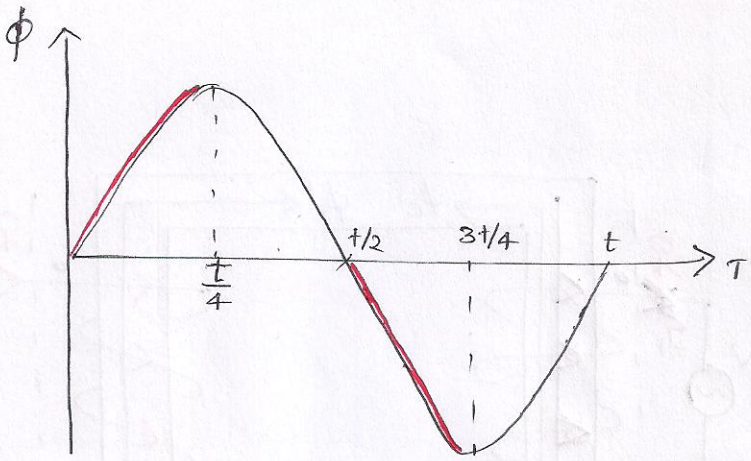
M +ve
Different Sense



M +ve
Same Sense

Begin – Top side
Termination – bottom side

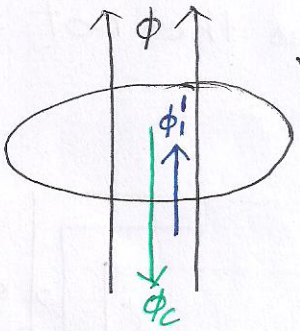
Note: M+ve, 't' of one coil is Connected to 'b' of other coil.
whether sense of winding varies.

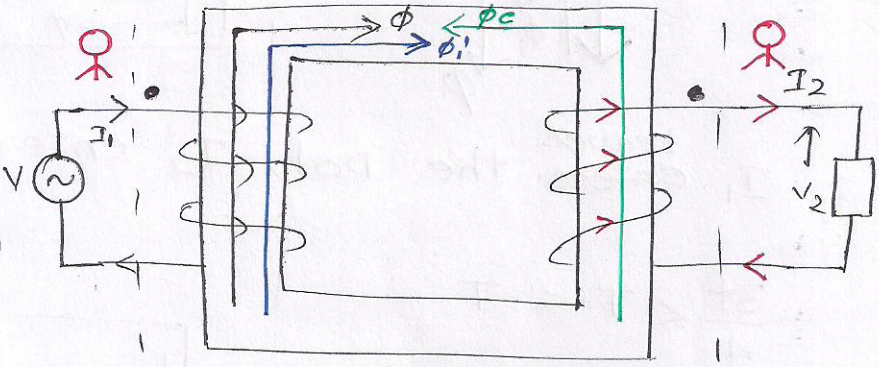


— Strengthening
— Weakening

Note: Current in Secondary depends on direction of ϕ_c / ϕ_2 only.

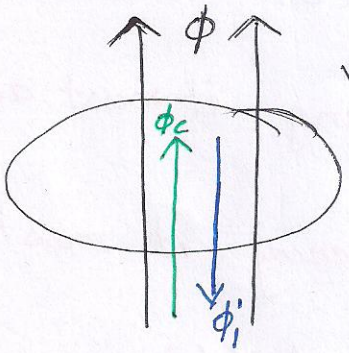
$0 < T < \frac{t}{4}$

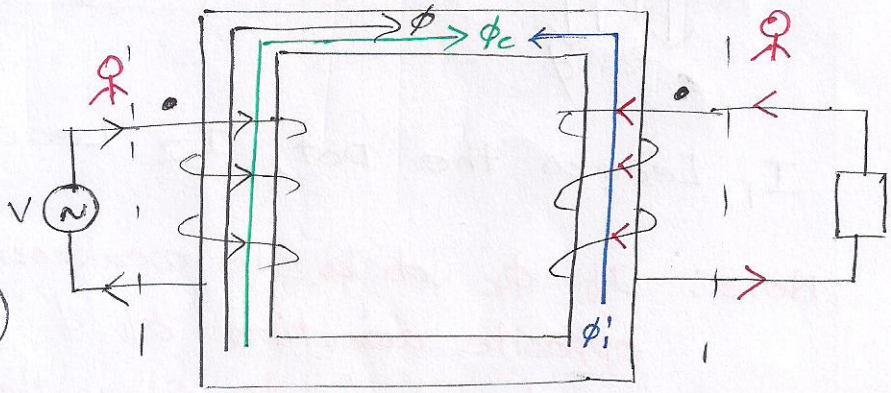




I_1 enters the Dot; I_2 Leaves the Dot ⇒ M-ve;

$\frac{t}{4} < T < \frac{t}{2}$





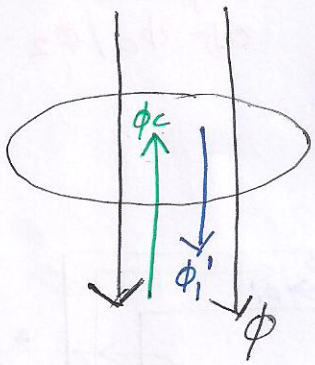
I_1 enters the Dot, I_2 ~~leaves~~ enters the Dot ⇒ M +ve

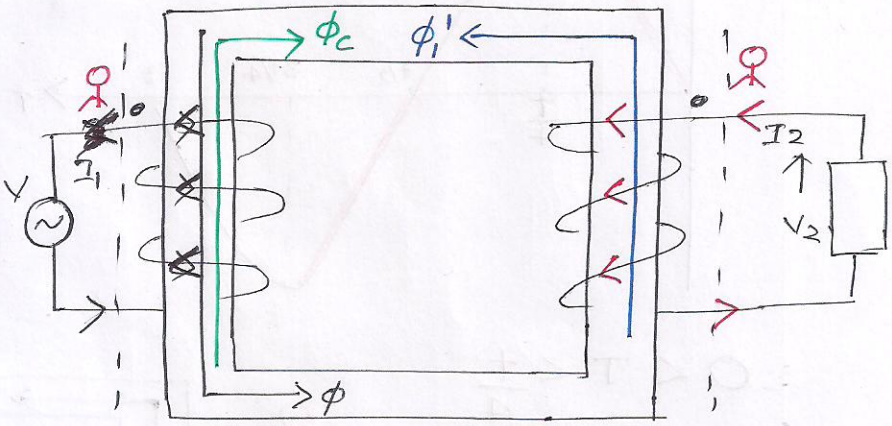
Note: During +ve half of ϕ, the direction is taken upward depending on interval $0 < T < t/4$ or $t/4 < T < \frac{t}{2}$ ϕ_c acts as per lenz law;

In 1st Quarter we have ϕ - strengthening: so as per lenz law ϕ_c must be weakening.

In 2nd Quarter ϕ - weakening so as per lenz law ϕ_c must be strengthening

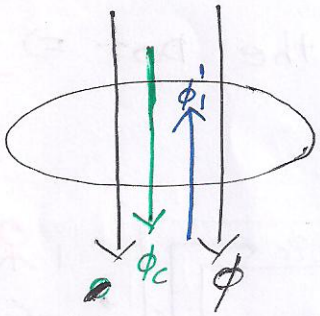
$\frac{t}{2} < T < \frac{3t}{4}$

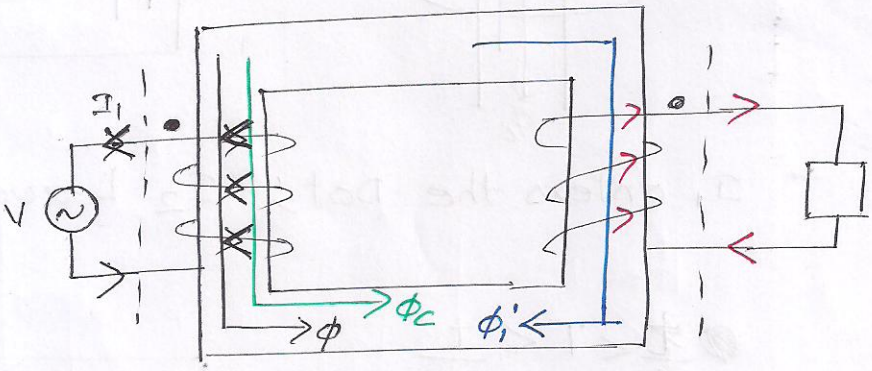




I_1 ~~enters~~ Leaves the Dot, I_2 enters the Dot ⇒ M -ve

$\frac{3t}{4} < T < T$





I_1 Leaves the Dot, I_2 Leaves the Dot ⇒ M+ve

Note: If ϕ_c job is to weakening it must act in opposite direction of ϕ

If ϕ_c job is to strengthening it must act in same direction of ϕ.

M value depends on ϕ, ϕ_2 (ϕ_c)

Current direction in secondary is obtained by ϕ_c applying Flemings Right Hand Rule.

Xmer Core

Material Silicon Steel (Electrical Steel)

→ Ferromagnetic material

→ High μ_r;

→ Low Hysteresis Coefficient (α)

$P_h = \eta B_{max}^{x} f V$

x Range 1.5 to 2.5

For Si steel $x = 1.6$;

Pure Steel

→ High μ_r

→ High Conductivity (σ) ⇒ More Eddy currents

Solution: ↓ in σ without effecting μ

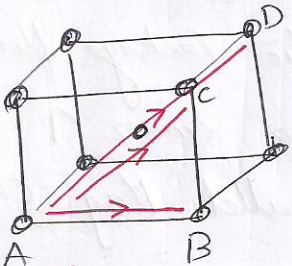
How: Add Silica about 4% - 5% in steel

If High proportion is used Brittleness↑

This just reduces we to further ↓

Lamcinitations are use making σ ↓ further

Silicon steel has B.C.C Structure. μ depends on individual permability of Grains (3 Types)

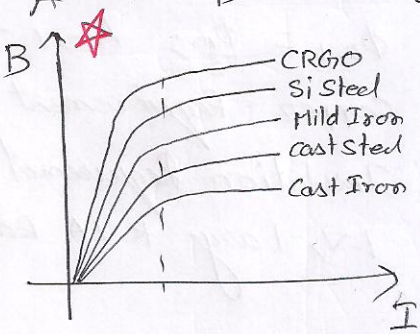


→ Along any of its 6 faces (A-B)

→ Diagonal of same faces (A-C)

→ Diagonal of opposite face (A-D)

$\mu_{AB} > \mu_{AC} > \mu_{AD} \Rightarrow I_{eAB} < I_{eAC} < I_{eAD}$



Si steel — 1.0 to 1.4
CRGO Steel — 1.6 to 1.8
} for same Excitation

$\phi = \uparrow B * A \downarrow$

Constant

CRGO Material has Less Area compared to Si steel Cas $B_{CRGO} > B_{Si\ steel}$;

Area ↓ ⇒ Less weight, Less Size.

Groos X-A → Core Material + Insulating Material
Net X-A → Core Material
99% of flux passes through core (Net X-A) as 'R'
of insulating material is High.

$B = \phi A_{Net}$; $A_g = l \times b$; $k_s = \frac{A_{Net}}{A_{Gross}}$ Range 0.5 to 0.95

Thick Lamcinations k_s – more
Thin Lamcinations k_s – less

If Lamcinations aren't properly staggered Air Gap Exist 'R'↑
For a constant ϕ, I must be high coz R↑ ↑MMF (NI) = ϕ R↑ const

Humming / Noise – Magnetostriction : Its tendency of magnetic material due to which slight change in Dimension take place under Alternating nature of Mag. force
Its a natural phenomenon.

Core Magnetized Lamination Thickness ↑
Core Demagnetized ↓

It cannot be avoided.

Compared with Square (⊙ coils) Core & Stepped Core (□ coils) mechanical strength is more in ⊙ Coils than □ Coils.

1) Core Type Xmer

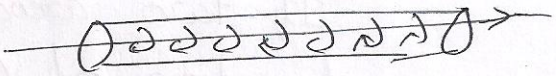
Mag. Leakage flux More
Power Xfor ↓
Series Mag. ckt
ϕ Same; A – Same
Copper Requirement More
Insulation Requirent less
HV, Small KVA Ratings

2) Shell Type Xmer

Magnetic Leakage flux less
Power xmer ↑
Parallel Mag. ckt
$\phi_{o,l} = \frac{\phi_m}{2}$; $A_{o,l} = \frac{A}{2}$;
Copper Requirement less
Insulation Requirenet more
LV, Large KVA Ratings

Transformer windings

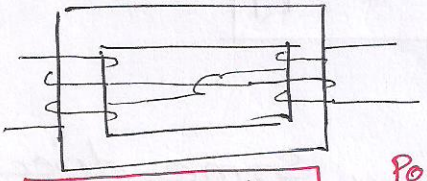
Aluminium — Distribution Xmer
Copper — Power Xmer



Single solid Conductors(A↑) → Stray losses Exists
Sol: Stranded Conductors, or Twisted; Strands electrically isolated (A↓). Also Skin effect can be minimized S.eff ∝ d^2

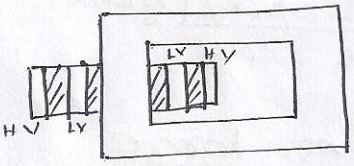
Windings in Core Xmer

a) Interleaving



ϕ_L↓, R↑, P↑

b) Concentric

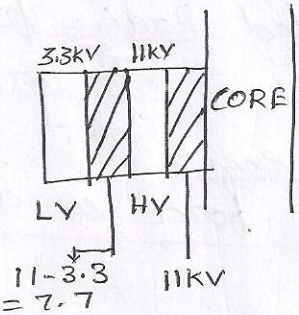


Power Transfer ∝ $\frac{1}{\phi_L}$

LV winding — High I — Thick wire; Less No. of Turns (L↓)
HV winding — Low I — Thin wire; More No. of Turn (L↑)

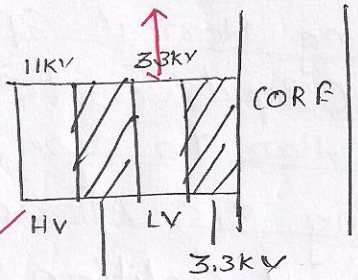
R_{HV} winding > R_{LV} winding $\left(R = \frac{\rho l}{A}\right)$

Core winding for 3.3KV/11KV Xmer



Total Insulation Thickness
= 18.7KV

LV winding – High I, Thick wire; (d_{LV})



Low I, Thin wire (d_{HV})

$d_{HV} < d_{LV}$

Total Insulation Thickness
= 11KV

∴ If LV is placed near core amount of insulation Reqd is Less.

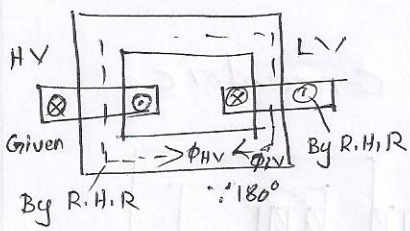
Due to this Dia of both LV, HV windings will be Reduced
⇒ Length per turn is Less;
∴ Amount of copper is less. Size, weight, cost ↓;

If LV winding is placed near to limb, distance between limb and wdg is Less compared to distance between limb and wdg when HV is placed near limb

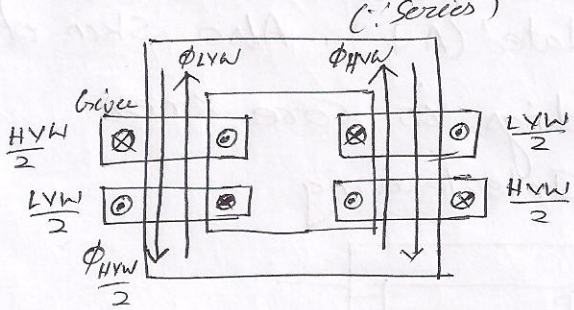
for Xmer Action, I_P, I_S must be 180°.

If two windings are placed on seperate limbs direction of current must be same.

If two windings are placed on same limbs the direction of current must be opposite



(∵ Series)



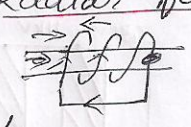
Lorenz force

If two ||rl conductors carry same direction of current Attractive force Exists

If two ||rl conductors carry different direction of current Repulsive force Exists

Note: Force Always Exists at weaker section only

During Normal operation $N_1 I_1 = N_2 I_2$ Net force Zero (Repulsive force) Also called Radiar forces as they are Har to core.



During S.C, Attraction forces Exists

Abnormal Condition $N_1 I_1 \neq N_2 I_2$ force is axial force and Radial force;

Sandwitching winding used in shell core

$\phi_l \downarrow$, $K \uparrow$, $P \uparrow$;

$P_{S.W} > P_{I.W}$

Interleaving $\phi_l = \frac{\phi_m}{2}$; Sandwitched winding $\phi_l = \frac{\phi}{4}$;

Placement of winding in core type Xmer – Horizontal

placement of winding in shell type Xmer – Vertical

Concentric winding structure requires more copper less insulation

Sandwitched winding structure requires less copper more insulation

$$\boxed{\text{Window factor} = \frac{\text{Height of window}}{\text{width of window}}}$$

Core Type Xmer $W\uparrow, H\downarrow, W.F\downarrow$

Shell Type Xmer $H\uparrow, W\downarrow$ W.F$\uparrow$

Ratio is more ⇒ less Leakage flux.

Auxiliary Parts

Silica Gel Placed @ breather so that Dry air is entered in Xmer making it moisture free so as to avoid deteriorate Insulating properties of Xmer oil.

Silica Gel – CaCl; Nrl Condition – Sky Blue; Abnormal/ Saturated Condition – Pale Pink;

Synthetic Oil is used as Xmer Oil (Chlorinated Deraphyl)

Desirable Properties of Xmer oil

→ Low viscosity : Helps in free movement so heat absorption takes place

→ High Dielectric Strength

→ free from moisture (Allowable water content < 30 PPM)

→ Xmer should have high Flash Point, Fire Point

→ Temparature at which oil → oil vapour (Flash Point)
(Generally >140°C)

→ Further ↑ in temp. oil vapour → oil flames
(Fire Point) (Generally >210°C)

Sludging: Decomposition of oil into small semi solid Hydro-Carbonates

Effect : settles on core, Damage of insulation takes place causing interturn fault

Bushings: Used to bring active leads from IN to OUT
Material used is porcleain

P_{Gr} ∝ volume; P_D ∝ Surface Area; ⇒ $P_D < P_{Gr}$

⇒ TT, Loading is limited;

↑ in effectiveness of cooling System makes ↑ in Rating of M/c

Types AN, AB, ON (Distribution Xmers), OB, OFC, OFB

Xmer Rating 10 / 16 MVA
ON Type OB Type

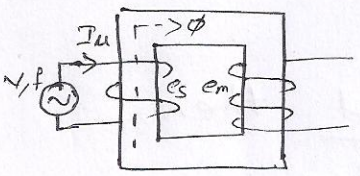
Explosion Vent

Under fault $I\uparrow$, $I^2R\uparrow (P_L)$, $T\uparrow$, Expansion of oil takes place Volume of oil $\uparrow$, Vent helps in gushing out of oil

Conservator is suitable for only load variations only.

Operation of Transformer

a) Finite μ_r viz $I_\mu \neq 0$; (finite)



$I_\mu = I_m \sin\omega t$

$\phi = \frac{MMF}{R} = \frac{N_1 I_m \sin\omega t}{R} = \phi_m \sin\omega t$

ϕ is time varying quantity $\Rightarrow$ Statically Induced Emf

Primary winding posses Self induced emf

Secondary winding posses Mutual induced emf

$e_1 = -N_1 \frac{d\phi}{dt} = N_1 \omega \phi_m \sin(\omega t - 90)$

e_1 is max @ $\omega t = 180°$; $e_1 = N_1 \omega \phi_m$

$K_S = \frac{A_{Net}}{A_{Gross}} = \frac{A_{Net}}{l \times b}$

$e_{1,rms} = \frac{e_{1,max}}{\sqrt{2}} = 4.44 \phi_m f N_1$;

$e_{1,rms} = 4.44 B_m * A_{Net} * f * N_1$

$e_2 = -N_2 \frac{d\phi}{dt} = N_2 \omega \phi_m \sin(\omega t - 90)$

$e_2/_{Max} = N_2 \omega \phi_m$; $e_{2,rms} = \frac{e_{2,max}}{\sqrt{2}} = 4.44 \phi_m f N_2$

$e_{2,rms} = 4.44 B_m A_{net} N_2 f$;

$\frac{e_1}{N_1} = \frac{e_2}{N_2} = 4.44 B_m A_{Net} f$

$\frac{e_2}{e_1} = \frac{N_2}{N_1} = K$ (Transformation Ratio)

Turn's Ratio

$N_1 : N_2 = E_1 : E_2$

$$\boxed{\text{Turn's Ratio} = \frac{1}{\text{Transformation Ratio}}}$$

★ 400/200 → Name Plate Details

Emf induced under No load (Not Applied / Terminal voltages

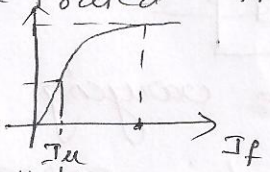
At every instant $v_1 = -e_1$ must be satisfied

$E_1 = 4.44 N_1 B_m A_{net} f$

$$B_m \propto \frac{E_1}{f} \propto \frac{V}{f}$$

Case 1: V constant; $f < f_{rated}$ then

$\uparrow B \propto \frac{V \to \text{constant}}{f \downarrow}$



$I_u \uparrow$ (Deep Saturation) 5% of I_{fl}

Overfluxing phenomenon which is undesirable.

Case 2; $B_{\text{Constant}} \propto \frac{V}{f} \Rightarrow V \propto f$

Design of Xmer

Rating = $E_1 I_1$ (Apparent Power)

$E \propto f \Rightarrow$ Rating $\propto f$

Ex: 100KVA, 60Hz when used at 50Hz rating is

$$\text{Rating}_n = \text{Rating}_o * \frac{f_n}{f_o} = 100 * \frac{50}{60} = 88 KVA$$

Case 1: If Rating, I of Xmer are fixed; Relation Between Effect on Size of Xmer;

(fixed) Rating = $E_1 I_1$ (fixed)

$\Rightarrow E_1 = \text{constant} = 4.44 B_m A_{net} N f$

$\Rightarrow B$ $A_{net} f = \text{Constant}$ ($A \downarrow$)

$\Rightarrow f \uparrow$, $A_{net} \downarrow \Rightarrow$ Size, weigh is Less;

Ex

a) 100 KVA, 25Hz (b) 100KVA, 50Hz (c) 100KVA, 30Hz

Small Size Xmer (b) Bulk Size (a)

Ex

a) 200 KVA 25 Hz b) 300 KVA, 75 Hz
c) 100 KVA, 50 Hz d) 400 KVA, 100 Hz

Note; If Ratings are different consider Specific weight

$$\text{Specific weight} = \frac{\text{weight of xmer}}{\text{KVA Rating}}$$

As seen earlier $f \uparrow, \omega t \downarrow \Rightarrow f \propto \frac{1}{\omega}$;

$$\text{Specific weight} = \frac{1}{f \times \text{KVA}}$$

Criteria factor

$\rightarrow f \uparrow, A \downarrow, \omega \downarrow$

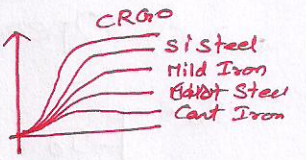
Ascending order of weight. D, B, C, A;

Case 2 ; Relation between Size of xmer on Bm A;

$$\text{Rating}_{\text{fixed}} = E_1 I_{1\,\text{fixed}}$$

$E_1 = 4.44 f N_1 B_m A_{net} \phi \Rightarrow B_m A_{net} = \text{constant}$

(E_1: constant; $4.44 f N_1$: constant)



$B_m \uparrow \quad A_{net} \downarrow$;

★ Descending order of Bm Materials

CRGO, Si steel, Mild steel, Cast steel, cast Iron

Descending order of size of xmer

Cast Iron, Cast steel, Mild Steel, Si steel, CRGO

b) Consider Iron losses (P_h, P_e)

Losses are to be supplied from source;

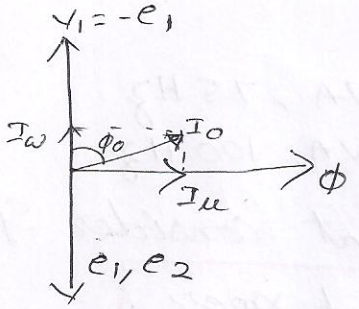
$I_\omega \rightarrow$ Iron Loss Component Supplied from Source

$I_0 = I_\mu + I_\omega$

$I_\mu \rightarrow 4\% - 5\%$ of I_{FL} (Wattless Component), I_μ quad with V

$I_\omega \rightarrow 1\% - 2\%$ of I_{FL} (Wattfull Component) I_ω in phase V

$I_0 = I_\omega - j I_\mu$;



I_0 Lags V_1 by ϕ_0

$\bar{I}_0 = |I_0| \angle -\phi_0 = I_0 \cos\phi_0 - j I_0 \sin\phi_0$

$I_0 \cos\phi_0 = I_\omega$; $I_0 \sin\phi_0 = I_\mu$

$I_0 = I_\omega - j I_\mu$,

No Load Power = $V_1 I_0 \cos\phi_0 = V_1 I_\omega$ = Iron Loses

Actually at No Load Small amount of $I_0^2 R$ Exists but I_0 (5% - 6% of $I_{f.L}$) is neglected.

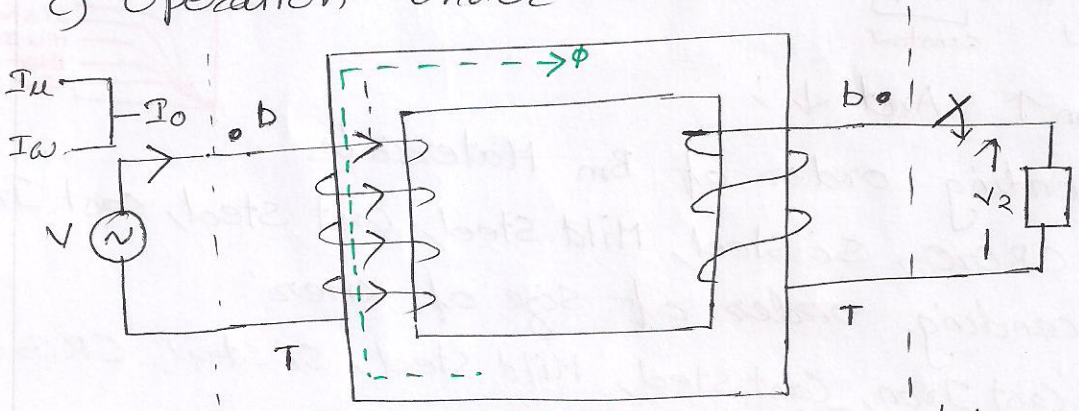
$R_0 = \frac{V}{I_\omega}$; $X_0 = \frac{V}{I_\mu}$; AA $I_\mu \gg I_\omega$ $R_0 \gg X_0$

Operation at Constant V, f ↓ ?

$\uparrow B = \frac{V - \text{constant}}{f \downarrow} \Rightarrow I_\mu \uparrow$ (Overflux phenomenon)

I_0 tends to I_μ ; $\phi_0 \uparrow$ $\cos\phi_0 \downarrow$

c) Operation Under Load



- First understand the sense of winding
- Assume Dot marks at beginning end of winding on both sides.
- Note : If the winding comes above the limb that end is ~~beginning~~ beginning the other side is termination

$N_1 I_\mu$ → Primary flux ;

$N_2 I_2$ → Secondary flux / Load component flux to be satisfied by Lenz Law. of Secondary

$N_1 I_1'$ — Load component flux of primary required to meet Load ;

I_1' & I_2 are displaced by 180°

$\Rightarrow \phi_1'$ & ϕ_2' are displaced by 180°

$$\phi_1' = \phi_2$$

$$N_1 I_1' = N_2 I_2$$

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = \frac{I_1'}{I_2} = K$$

$\Rightarrow E_1 I_1' = E_2 I_2$

Load Component of Primary VA = Load Component of Secondary VA

Approximate Relationships

$\bar{I}_1 = \bar{I}_0 + \bar{I}_1'$

$\bar{I}_1 \simeq I_1' \Rightarrow N_1 I_1 \simeq N_2 I_2 \Rightarrow K = \frac{I_1}{I_2}$;

$E_1 I_1 \simeq E_2 I_2 \Rightarrow$ Constant Power Device.

*Primary P.f can be unity @ R-C Load only.

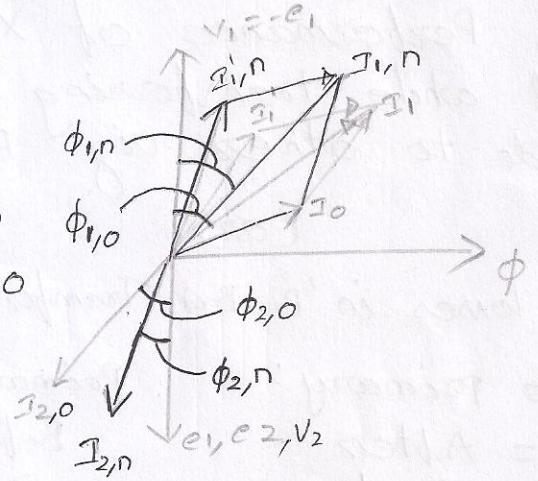
If $\cos\phi_2$ Increases at Lag, what is $\cos\phi_1$?

$\phi_{1,o} > \phi_{1,n}$

$\cos\phi_{1,o} < \cos\phi_{1,n}$

$\cos\phi_{1,n} > \cos\phi_{1,o}$

$\cos\phi_1 \uparrow$;



$\phi_{2,o} > \phi_{2,n}$

$\cos\phi_{2,n} > \cos\phi_{2,o}$

viz $\cos\phi_2 \uparrow$

P.f of lag load on Secondary ↑, Primary P.f ↑

viz if P.f on Secondary improves, P.f on Primary improves, @ Lag Load.

If $\cos\phi_2 \uparrow$ (Lead) what is $\cos\phi_1$?

$\phi_{2,n} < \phi_{2,0}$

$\cos\phi_{2,n} > \cos\phi_{2,0}$

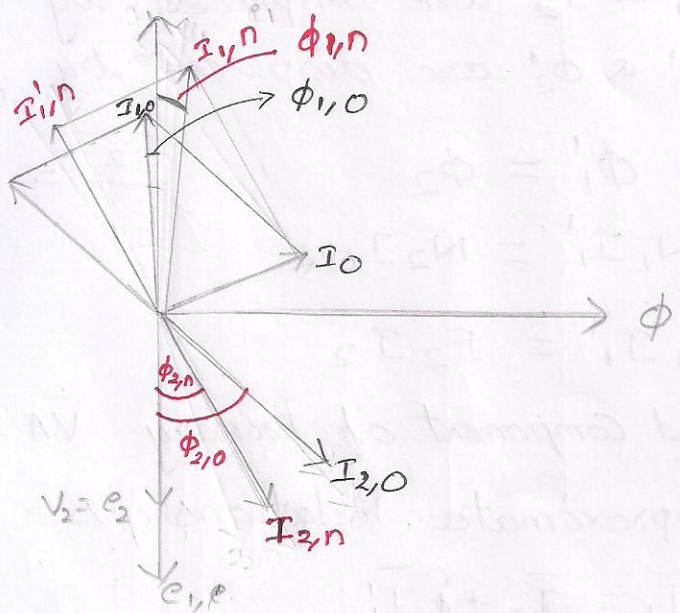
viz $\uparrow$ in $\cos\phi_2$

$\Leftrightarrow$

$\phi_{1,0} < \phi_{1,n}$

$\cos\phi_{1,n} < \cos\phi_{1,0}$

viz $\downarrow$ in $\cos\phi_1$



P.f of Lead Load on secondary $\uparrow$, Pcimary P.f will $\downarrow$

P.f on secondary improves, P.f on primary deteriorates @ Lead load.

d) Effect of winding Resistance;

$$\bar{V}_1 = -\bar{E}_1 + \bar{I}_1 R_1 \; ; \quad \bar{E}_2 = \bar{I}_2 R_2 + \bar{V}_2$$

$$P_{T(Cu)} = I_1^2 R_1 + I_2^2 R_2$$

Condition: Performance of Xmer shouldn't be affected while transferring Resistance from one side to other viz P.L must be maintained constant.

(or)

Copper losses in 'R' B4 Transfer = Copper losses in 'R' After Transfer

Secondary to pcimary:

Before = After

$I_2^2 R_2 = I_1^2 R_2'$

$R_2' = R_2 \left(\frac{I_2}{I_1}\right)^2 = \frac{R_2}{k^2}$

Pcimary to Secondary

Before = After

$I_1^2 R_1 = I_2^2 R_1'$

$R_1' = \left(\frac{I_1}{I_2}\right)^2 R_1 = k^2 R_1$

$R_{01} = R_1 + R_2' = R_1 + \frac{R_2}{k^2}$

$R_{02} = R_2 + R_1' = R_2 + k^2 R_1$

Total Cu. Los w.r.t primary $= I_1^2 R_{01}$

Total Cu. los w.r.t Secondary $= I_2^2 R_{02}$

$I_1^2 R_{01} = I_2^2 R_{02}$

P.U Resistance Primary Drop $= \frac{I_1 R_1}{E_1}$

P.U Secondary Resistance Drop $= \frac{I_2 R_2}{E_2}$

Total P.U Resistance Drop w.r.t primary $= \frac{I_1 R_{01}}{E_1}$

Total P.U Resistance Drop w.r.t Secondary $= \frac{I_2 R_{02}}{E_2}$

**P.U Resistance Drop w.r.t primary =
P.U Resistance Drop w.r.t Secondary

**P.U Resistance Drop = P.U Resistance of Xmer

∴ % R of Xmer w.r.t primary $= \frac{I_1 R_{01}}{E_1} \times 100$

% R of Xmer w.r.t Secondary $= \frac{I_2 R_{02}}{E_2} \times 100$

% R on Both sides of Xmer is Same (Always)

e) Effect of Magnetic Leakage

→ Leakage flux is part of load component of flux (ϕ_1' or ϕ_2) which passes through air & n't through core.

→ Leakag flux either links with HV (or) LV but n't Both

→ It doesn't involve in power Transfer

→ Condition for power Transfer $\phi_1' = \phi_2$

→ To Minimiz ϕ_ℓ Employ Interleaving (or) Concentric winding for Core Type xmer & Sandwitched winding in Shell Type Xmer.

If load is Increased

ϕ →

$\phi_1' = 100\%$ ← $\phi_2 = 120$

$\phi_{Net} = -20\%$

$\phi_{Net} \downarrow$ $E_1 \downarrow$

Primary voltage $(V_1 - E_1) \uparrow$

Producing $\uparrow$ in I_p to produce Add. Primary MMF

$\phi_1' \uparrow$ Now $\phi_1' = 120 = \phi_2$

If load is Decreased

ϕ →

$\phi_1' = 100$ → ← $\phi_2 = 90\%$

$\phi_{Net} = +10\%$

$\phi_{Net} \uparrow$, $E_1 \uparrow$ $(V_1 - E_1) \downarrow$

Producing $\downarrow$ in I_p to produce decreased MMF such that

$\phi_1' = 90\% = \phi_2$

As $\phi_1' \gg \phi_{l1}$ major contribution is ϕ_1'

ϕ_{l2} only contribution is ϕ_2

Leakage flux isn't constant & depends on load current on respective winding but n't on voltage

Main field is independent of load current & depends only on V/f Ratio

At No Load $I_2 = 0$; ~~$I_1' = 0$~~ $\therefore \phi_{l2} = 0$

$I_1' = K I_2 = 0 \Rightarrow \phi_{l1}$ contibution is by I_0 only which depends on V/f

$\phi_{l1} = f(I_1) = f(I_0 \& I_1')$; $\phi_{l2} = f(I_2)$

As

Leakage fluxes are always in phase with currents in windings.

Refer P.g. No 33 for vector diagram.

$\bar{V}_1 = -\bar{E}_1 + j\bar{I}_1 X_1$; $\bar{E}_2 = \bar{V}_2 + j\bar{I}_2 X_2$

$\bar{V}_1 = -\bar{E}_1 + \bar{I}_1 Z_1$; $\bar{E}_2 = \bar{V}_2 + \bar{I}_2 Z_2$

$E_1 \rightarrow$ Self Induced Emf ; $E_2 \rightarrow$ Mutual Induced Emf

Condition : P.U Reactance Drop must be maintained Constant

(OR)

P.U Reactance Drop ~~is~~ Before Transfer = P.U Reactance Drop After Transfer

P.U Reactance Drop in Primary $= \frac{I_1 X_1}{E_1}$

P.U Reactance Drop in Secondary $= \frac{I_2 X_2}{E_2}$

Secondary to Primary

Before After

$$\frac{I_2 X_2}{E_2} = \frac{I_1 X_2'}{E_1}$$

$$X_2' = X_2\left(\frac{E_1}{E_2}\right)\left(\frac{I_2}{I_1}\right)$$

$$X_2' = X_2/k^2$$

$$X_{01} = X_1 + X_2' = X_1 + \frac{X_2}{k^2}$$

Primary to Secondary

Before After

$$\frac{I_1 X_1}{E_1} = \frac{I_2' X_1'}{E_2}$$

$$X_1' = X_1\left(\frac{I_1'}{I_2}\right)\left(\frac{E_2}{E_1}\right)$$

$$X_1' = X_1(k^2)$$

$$X_{02} = X_2 + X_1' = X_2 + X_1(k^2)$$

Total P.U x Drop w.r.t primary $= \frac{I_1 X_{01}}{E_1}$

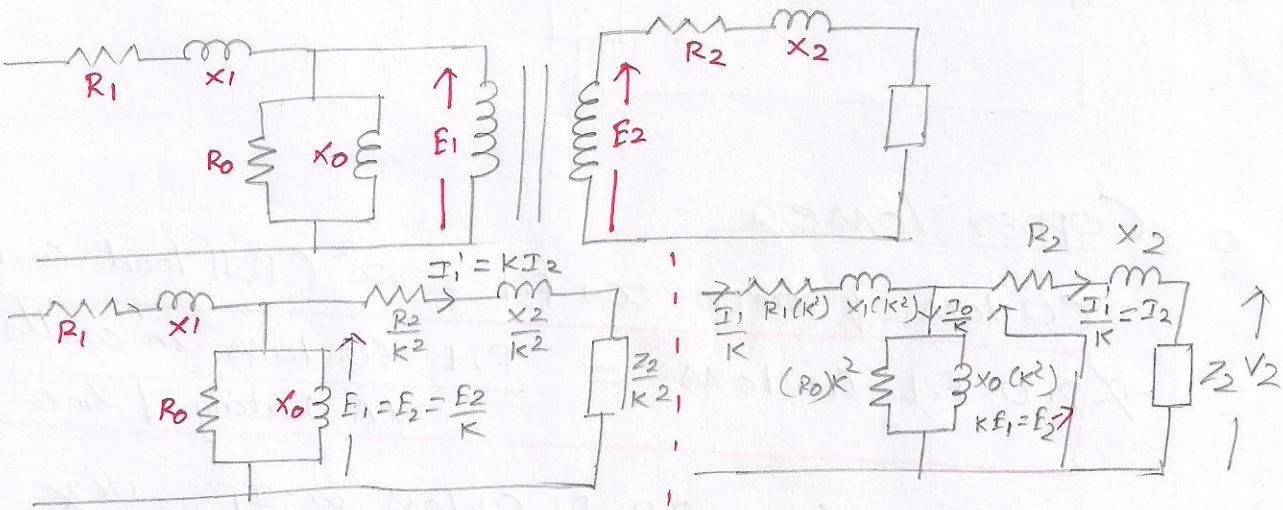
Total P.U x Drop w.r.t Secondary $= \frac{I_1 X_{02}}{E_2}$

P.U x Drop on bothe side is always same

** P.U Reactance Drop = P.U Reactance of Xmer

% P.U Reactance of Xmer w.r.t primary $= \frac{I_1 X_{01}}{E_1} \times 100$

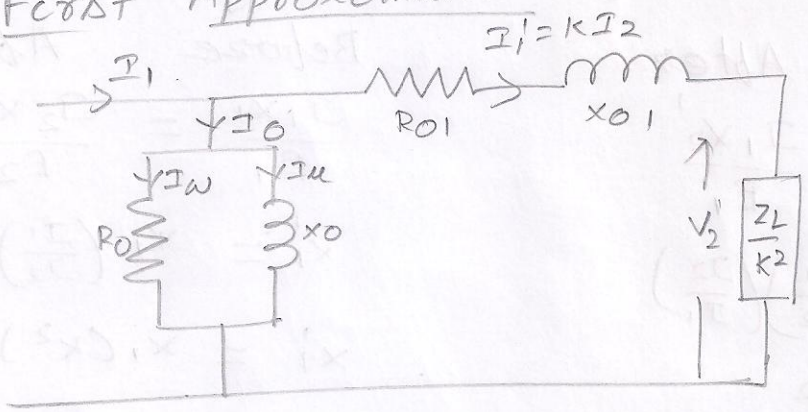
% P.U Reactance of Xmer w.r.t $\frac{\text{Secondary}}{\text{Primary}} = \frac{I_2 X_{02}}{E_2} \times 100$



$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = K \qquad \frac{I_1}{I_2} = K$$

$$\boxed{E_1 = \frac{E_2}{K}} \qquad \boxed{I_1 = KI_2}$$

First Approximation



$\uparrow I_0 = \frac{\checkmark (\uparrow)}{(R_0 \| \omega X_0)}$

Deviations

→ $I_0 Z_1$ is neglected ★

→ $I_0^2 R_1$ is neglected (P_{cu} underestimated)

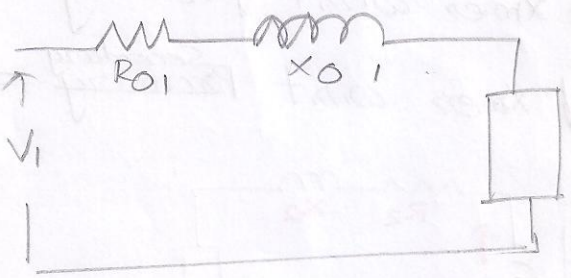
→ ϕ_{L1} due to I_0 neglected

→ $V_1 > E_1 \Rightarrow I_0 \uparrow \Rightarrow I_w \uparrow, I_u \uparrow \Rightarrow$ ★ P_i overestimated

→ As I_0 is 5% of I_{FL} error's are very small

Second Approximation

I_0 neglected:



Copper losses

Cu loss of xmer x * F.L $= x^2$ (Full load Cu. loss)

★ P.U F.L Cu. loss $= \frac{\text{F.L Cu. loss in watts}}{\text{VA Rating of Xmer}} = \frac{I_1^2 R_{01}}{\text{VA Rating}}$

For a given xmer P.U F.L Cu. loss $\propto I_1^2$ viz

P.U Cu loss of xmer at x. F.L $= x^2$ (P.U Full load Cu. loss)

P.U Resistance Drop w.r.t primary $= \frac{I_1^2 R_{01}}{E_1} * \frac{I_1}{I_1}$

$= \frac{I_1^2 R_{01}}{E_1 I_1}$

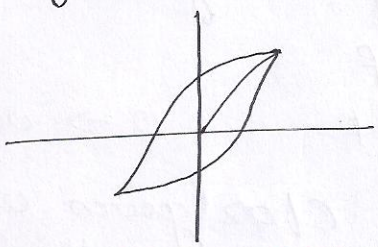
P.U Resistance ~~Drop~~ of Xmer w.r.t primary =

$\frac{\text{Full load Cu. Lons}}{\text{VA Rating of Xmer}}$ = P.U F.L Cu lons

⇒ ***% F.L Cu lons = % R of Transformer

Iron losses

a) Hysteresis Lons



Hysteresis lons/cycle = Area enclosed within one Hysteresis Loop

For 50Hz Loop is Repeated 50 times

Total Hysteresis lons = 50 {Area enclosed within one Hysteresis Loop}

$W_h = \eta B_{max}^{x} V f$ (V: volume)

⇒ Area enclosed in one Hysteresis loop = $\eta B_{max}^{x} V$

Area $\propto B_{max}^{x}$ (for a given core)

$B_{max} \propto V/f$

Area $\propto (V/f)^{x}$

With ↑ in Bmax, Height ↑, width remains constant
viz vertical expansion takes place

With constant Bmax, Height constant, V ↑, width ↑
viz Horizontal Expansion takes place.

* Height Determined by Bmax
* Width Determined by volume

Variations of Hysteresis Loss

Case 1 : $\frac{V}{f}$ const

$\Rightarrow$ B_{max} const $\Rightarrow$ ~~Width~~ Height Remains Constant

for a given Core volume const $\Rightarrow$ Width Remains Constant

$\therefore$ Area (Hysteresis Loop) remains constant Area = $B_{max}^{x} * v$ (Height, width)

$W_h \propto f$ (Independent of voltage Variations)

Case 2 : $\frac{V}{f} \neq$ const

$B_{max} \neq$ const; $\Rightarrow$ Height $\neq$ constant (↓ or ↑)

$\therefore$ Area enclosed by one Hysteresis Loop $\neq$ constant

$W_h \propto (Area) * f$

$W_h \propto (B_{max}^{x} V) * f$ $v \rightarrow$ volume

$W_h \propto B_{max}^{x} f$ (for given volume)

$W_h \propto \left(\frac{V}{f}\right)^{x} f$

$$\boxed{W_h \propto V^{x} f^{1-x}}$$

For CRGO steel $x = 1.6$

$W_h \propto V^{1.6} f^{-0.6}$ (V → Voltage)

$$\Rightarrow \boxed{W_h = A V^{1.6} f^{-0.6}}$$

Case 3 ; V → constant $f < f_{rated}$ effect on W_h

$\frac{V}{f} \neq$ constant, $B_{max} \neq$ constant, Height $\neq$ constant

~~B_{max}~~ $W_h \propto$ Area $* f$

$W_h \propto B_{max}^{x} V * f$ (v - volume)

$W_h \propto B_{max}^{x} f$ (For ~~At~~ given volume)

$\uparrow B_{max} \propto \frac{V \rightarrow \text{constant}}{f \downarrow}$

$\Rightarrow B_{max} \neq$ const;

$\therefore W_h \propto \left(\frac{V}{f}\right)^{x} f$

$$\boxed{W_h \propto f^{1-x}}$$

C.: voltage is constant

b) Eddy Current losses

$\sigma \rightarrow$ Conductivity
$\rho \rightarrow$ Resistivity
$R = \frac{\rho l}{A}$

$$\text{Losses} = I_e^2 R_{ce}$$

$$I \propto \sigma; \quad R_{ce} \propto \rho \propto \frac{1}{\sigma}$$

$$\text{Losses} \propto \sigma^2 * \frac{1}{\sigma} \Rightarrow \text{Losses} \propto \sigma;$$

$w_e \propto \sigma$ $\quad \downarrow \sigma$ (Conductivity) $\quad w_e \downarrow$; Used Laminati

$$w_e = K B_{max}^2 f^2 t^2 \qquad K = \frac{\pi^2}{6\rho} = \frac{\pi^2 \sigma}{6}$$

Thin Lamination are costly, CRGO (preferred)

To make constant w_e

$$w_e = K B_{max}^2 f^2 t^2 \Rightarrow f^2 t^2 = \text{constant}$$

(Constant)

High 'f' Xmer thin Laminations; low f xmer thick Lamination

Ex Transformer 1 @ 50 Hz Transformer 2 @ 60 Hz

$f_1 < f_2 \Rightarrow$ Transformer 1 uses Thicker Laminati

Transformer 2 uses Thinner Lamination.

$$K_S = \frac{A_{Net}}{A_{Gross}} = \frac{(\text{Magnetic Material}) \text{ Area}}{(\text{Magnetic Material} + \text{Lamination}) \text{ Area}}$$

XFor Trans form 1 Agross is more compared to Transfor 2;

$$X K_S \propto \frac{1}{A_{Gross}}; \quad A_{Gross\,1} > A_{Gross\,2}$$

$X \Rightarrow K_{S,1} < K_{S,2}$;

→ Thick Laminations K_S is more
→ Thin Laminations K_S is less

Variations of Eddy Current Loss

Case 1 : $\frac{V}{f}$ const

$\Rightarrow B_{max}$ constant $\quad W_e \propto f^2 \Rightarrow W_e = Bf^2$

for a given xmer

Case 2 : $\frac{V}{f} \neq$ const

$\Rightarrow B_{max} \neq$ constant $\quad W_e \propto B_{max}^2 f^2 \propto \left(\frac{V}{f}\right)^2 f^2$

$\Rightarrow W_e \propto V^2 \Rightarrow W_e = CV^2$; (Independant of frequency)

Case 3 : V Constant, $f < f_{rated}$ $W_e = ?$

$\uparrow B_{max} \propto \frac{V \rightarrow \text{constant}}{f \downarrow}$

$B_{max} \neq$ constant

$W_e \propto \left(\frac{V}{f}\right)^2 \times f^2 \quad W_e \propto V^2 \rightarrow$ constant

W_e is constant; as V is constant in this case

At Norm Constant Operation (Voltage)

$W_h \propto f^{-0.6}$; W_e = constant

$W_i = W_h + W_e = A(f^{-0.6}) + B$

W_i is independent of current ~~& voltage~~

W_i is constant at Normal Operation

★ P.U Iron loss = $\frac{\text{Iron Loss in watts}}{\text{VA Rating of Xmer}}$

Stray losses – variable losses

a) Copper stray loss

$I_s^2 R_{CS}$

Strands are used

enamel paint seperates them

I_s is part of load current

b) Iron Stray losses

ϕ_L is Reason

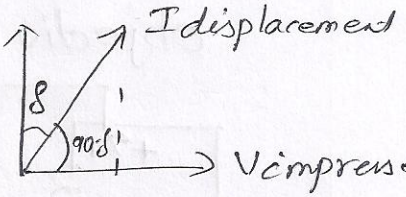
ϕ_L depends on load current (I_1, I_2)

Dielectric loss ; Due to imperfection of Materials

Pure Dielectric

Dielectric loss = 0

Practical Dielection



Loss = V impressed I displ Cos(90-δ)

Loss = V impressed I displacent Sinδ

Tan δ = Dissipation factor

↑ Tan δ Poor Material

↓ Tan δ Good Material

Dielectric loss is independent of load current and depends on applied voltage.

0.25 % of F.L O/P

Constant Losses

a) Pi b) Dielectric Losses

Both depends on voltage

Variable losses

a) Pcu b) Stray load losses

Both depends on load current

Testing of Xmers

→ Polarity Test

→ O.C Test

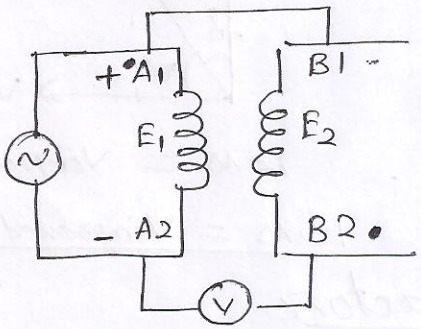
→ S.C Test

→ Sompner's Test

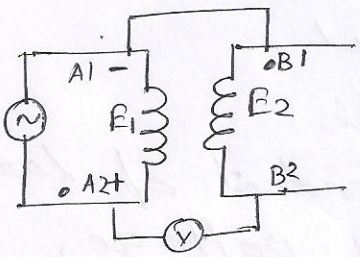
Polarity Test

a) First Method

Objective: To find Dot Marks

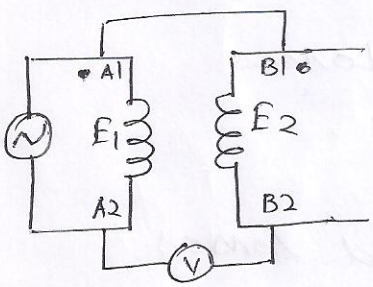


If V Reads $E_1 + E_2$
Series additive polarity
then B1 (-) B2 (+)



Now Assume A_1 is at (-) A_2 (+)
for a particular instant
If V Reads $E_1 + E_2$
B_1 (+) B_2 (-)

Hence if V Reads $E_1 + E_2$ Pair of dissimilar terminals become dotted



If
Assume A1 (+) A_2 (-)
V reads $E_1 - E_2$ Series subtractive polarity then
B_1 (+) B_2 (-)

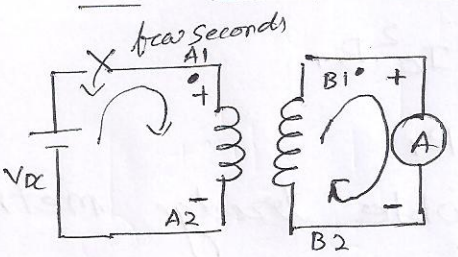
If A1 (-) A_2 (+) $V = E_1 - E_2$ B_1 (+) B_2 (+)

Hence if V Reads $E_1 - E_2$ Pair of Similar terminals become dotted

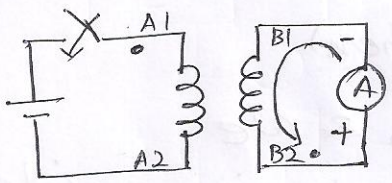
Disadvantage: Difficult to conduct test on HV xmer

b) Second Method

DC kick Test



If pointer has forward kick then flow of 'i' in Secondary is Clockwise
Pair of similar terminals should have dot for Fwd kick



If pointer has backward kick then flow is in ACW;
pair of Dissimilar terminals should be dotted for Bwd kick

O.C Test

→ To find R_0, X_0, Pconstant, Ph, Pe

Procedure

→ One wdg is kept @ Rated V, f with other wdg open

rated $B \propto \frac{V_{rated}}{f_{rated}}$

→ Preferably perform Test on LV with HV open

Ex 2000/200 50 Hz xmer

	HV	LV	
I_{FL}	10	100	CK must be satisfied
I_o (5% of I_{FL})	0.5	5A	

Easier to measure 5A than 0.5A ; % Test Performed on LV side preferably.

Generally $\cos\phi_o$ Range 0.20 to 0.25

$\cos\phi_o < 0.5 \Rightarrow$ LPF wattmeter is Used

$R_0 = \frac{V}{I_w}$; $X_0 = \frac{V}{I_u}$; $I_w = I_0 \cos\phi_0$; $I_u = I_0 \sin\phi_0$

$W_0 = V_1 I_0 \cos\phi_0$ = No load pow;

$\cos\phi_0 = \frac{W}{V \cdot I_0}$

$W_0 = P_i$ + Dielectric loss + $I_0^2 R_1$

Constant Losses = $W_0 - I_0^2 R_1$

For R_1 use kelvin Double bridge method as its order is very Low;

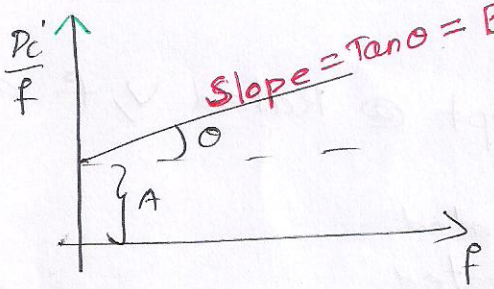
$W_0 \simeq P_i$ (neglecting others)

Seperation of P_i for W_h & W_e

→ Apply V.V.V.f such that V/f is maintained constant

$\Rightarrow$ Bmax = Constant

$P_i = Af + Bf^2$ $\qquad \frac{P_i}{f} = A + Bf$



Slope of line = Tanθ = B

W_h(rated) = A frated

W_e(rated) = B f^2rated

Ex for 400/200V 50 Hz Transformer Test are done

O.C Test (LV) 200V, 50Hz $W_i = 100$

O.C Test (HV) 200V, 50Hz $W_i = ?$

Sol:- O C Test is performed at Rated voltage & Rated frequency:

Rated values are applied on LV side $W_i = 100$

if // // on HV side viz

V = 400V, f = 50Hz W_i = 100 watts

But applied voltage is 200V, f = 50Hz

$\downarrow B_{max} \propto \frac{V\downarrow}{f-\text{constant}} \Rightarrow B_{max} \neq \text{constant}$

$w_h \propto B_{max}^{x} f \qquad w_e \propto B_{max}^{2} f^2$

$w_h \propto \left(\frac{V}{f}\right)^x f \qquad w_e \propto \left(\frac{V}{f}\right)^2 f^2$

At constant frequency

$w_h \propto V^x \qquad w_e \propto V^2$

$x = 1.6$ Let x be 2.0:

$w_h \propto V^2 \qquad w_e \propto V^2$

$\boxed{w_i \propto V^2}$

$w_{i,2} = w_{i,1}\left(\frac{V_2}{V_1}\right)^2 = 100\left(\frac{200}{400}\right) = 25w;$

Ex 400/200 50 Hz Test is performed on xmer

OC Test(LV) 200V 50Hz $w_i' = 100$

OC Test(HV) 200V 25Hz $w_i' = ?$

w_i' are equally divided @ Rated V, f;

Sol:- OC Test is performed(LV) at Rated V, f and $w_i' = 100$

if Test is performed at Rated V, f on HV $w_i' = 100$

Losses are equally distributed $\Rightarrow w_h = 50 = w_e$;

$\frac{400}{50} = \frac{200}{25} \Rightarrow B_m$ constant

$w_h \propto f; \quad w_e \propto f^2$

$w_{h2} = 50\left(\frac{25}{50}\right) = 25; \qquad w_{e2} = 50\left(\frac{25}{50}\right)^2 = 12.5$

$w_i' = 37.5w;$

→ V - Rated; f < frated; Effect on Parameters

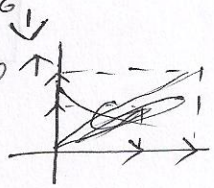
$\uparrow B_{max} \propto \frac{V}{f\downarrow} \Rightarrow I_u \uparrow$ (Over flux phenomenon)

$B_{max} \neq$ constant $w_h \propto V^{1.6} f^{0.6} \Rightarrow \uparrow w_h \propto f^{-0.6}\downarrow$

$w_e \propto V^2 \Rightarrow w_e =$ constant $\Rightarrow w_i \uparrow \Rightarrow I_w \uparrow$

$\uparrow \bar{I}_0 = \bar{I}_u + \bar{I}_w \quad \uparrow w_0 \simeq w_i \uparrow \quad \cos\phi_0 = \frac{w_0}{V I_0}$

$\cos\phi_0 \downarrow$ (prove it by vector diagram only)



S.C Test

→ To find Variable losses, R_{eq}, X_{eq}, %R, %X, %Z of xmer

Procedure

→ LVW is S.C through wire of same dia as that of LV winding

→ Rated S.C Current I_{sc} = I_{fl} @ Reduced Rated Voltage

Steady S.C current = I_{fl} @ Rated Voltage

→ Apply Reduced V, @ Rated f & Rated current flows in both windings

→ Prefer LV S.C

→ V_{sc} (5% to 8%) of V_i Rated.

o/p power = 0 (∵ S.C)

W_{sc} = F.L C.U LOSS + Stray load loss + Small amount of W_i

Variable losses = W_{sc} − Small amount of W_i @ Reduced voltage

Small amount of W_i @ Reduced Voltage can be obtained from O.C Test.

As in S.C Test V ↓, f constant;

Bm ≠ constant $W_h \propto \left(\frac{V}{f}\right)^{1.6} f$ $W_e \propto \left(\frac{V}{f}\right)^2 f^2$

$W_h \propto V^{1.6}$; $W_e \propto V^2$ ⇒ $W_i \propto V^2$

$$\frac{W_{i,\text{Red.V}}}{W_{i,\text{Rat.V}}} = \left(\frac{V_{red.}}{V_{rat.}}\right)^2 = \left(\frac{V_{SC}}{V_{rated}}\right)^2;$$

$W_{sc} \simeq$ F.L CU LOSS; (neglecting others)

∴ $W_{sc} \simeq I_{sc}^2 R_{01}$ (∵ F.L CU LOSS)

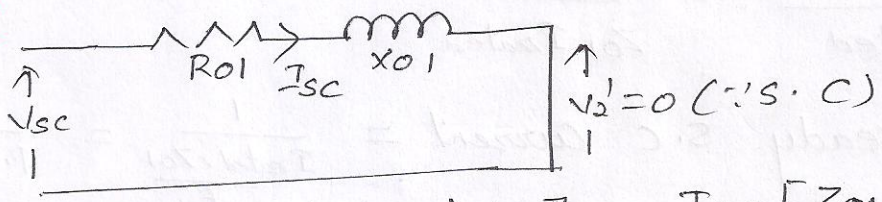
$$\boxed{R_{01} = \frac{W_{sc}}{I_{sc}^2}}$$

Since Rated Voltage isn't applied I_o is negligible

$R_o = \frac{V}{I_w}$; $X_o = \frac{V}{I_u}$ $\quad I_w = I_o \cos\phi \quad I_u = I_o \sin\phi$

as $I_o \simeq 0$; $\quad R_o = \infty$; $\quad X_o = 0$;

In this case $R_{eq} = R_{01}$



$V_{SC} = I_{SC}[R_{01} + jX_{01}] = I_{SC}[Z_{01}]$

$\Rightarrow Z_{01} = \frac{V_{SC}}{I_{SC}}$; $\quad X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$

$R_{01} < X_{01}$;

Note: Ascending order $\boxed{R_{01} < X_{01} < X_o < R_o}$

$R_1 \simeq R_2' < X_1 \simeq X_2' < X_o < R_o$

We know % R of Xmer = % F.L Cu Loss;

$$\% R \text{ of Xmer} = \frac{\text{Full Load Cu. Loss}}{\text{VA Rating}} \times 100$$

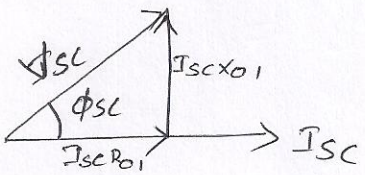
$$= \frac{W_{SC}}{VA} \times 100;$$

We know $V_{SC} = I_{SC} \angle \phi_1$

$$Z_{01} = \frac{V_{SC}}{I_{SC}}$$

$$\% Z = \frac{I_{SC} Z_{01}}{E_1} = \frac{V_{SC}}{E_1}$$

$$\% X = \sqrt{(\% Z)^2 - (\% R)^2}$$



$\boxed{V_{SC} = I_{SC} Z_{01}}$;

$\phi_{SC} = \tan^{-1}\left(\frac{X_{01}}{R_{01}}\right)$ Lag always

$\boxed{\cos\phi_{SC} = \frac{R_{01}}{Z_{01}} = \frac{\% R}{\% Z}}$

$\cos\phi_{SC} \simeq 0.5$ to 0.6 Lag

OPF meter is used (∵ p.f > 0.5)

$$I_{s.c\,(steady)} = \frac{E_1}{Z_{01}}$$

$$\frac{I_{s.c\,(steady)}}{I_{rated}} = \frac{E_1}{Z_{01}\, I_{rated}}$$

$$P.U \text{ steady } S.C \text{ current} = \frac{1}{\frac{I_{rated} \times Z_{01}}{E_1}} = \frac{1}{P.U\,Z}$$

→ V_{SC} → constant, $f < f_{rated}$ Effect on Parameter (S.C Test)

R_{01} — Constant

$X_{01} \downarrow$, $Z_{01} \downarrow$;

$$\uparrow I_{SC} = \frac{V_{SC}}{Z_{01}\downarrow} \qquad \uparrow W_{SC} = \uparrow I_{SC}^2 R_{01}$$

$$\uparrow \cos\phi_{SC} = \frac{R_{01} - \text{constant}}{Z_{01}\downarrow}$$

Performance Indices of Transformer

→ Efficiency - P

→ Voltage Regulation - Q

Efficiency of Transformer

$$\eta = \frac{o/p}{i/p} \qquad \eta_{F.L} = \frac{E_2 I_2 \cos\phi_2}{E_2 I_2 \cos\phi_2 + P_i + I_2^2 R_{02}}$$

$$\eta_{x \text{ of } F.L} = \frac{E_2 (xI_2) \cos\phi_2}{E_2 (xI_2) \cos\phi_2 + P_i + (xI_2)^2 R_{02}}$$

$$\eta_{x.\text{ of } F.L} = \frac{1}{1 + \frac{P_i + (xI_2)^2 R_{02}}{xE_2 I_2 \cos\phi_2}}$$

$\frac{\text{Losses}}{\text{o/p power}}$

Condition For Maximum Efficiency

a) $\left.\frac{d\eta}{d(xI_2)}\right|_{\substack{\text{constant}\\ \phi_2}} = 0$

b) $\left.\frac{d\eta}{d\phi_2}\right|_{\substack{\text{constant}\\ xI_2}} = 0$

a) $\left.\frac{d\eta}{d(xI_2)}\right|_{\substack{\text{constant}\\ \phi_2}}$ is Maximum when Denomcinator is Min.

viz $\frac{\text{Losses}}{\text{Polp}}$ is Min;

Happen's when CU LOSS = Iron LOSS

$$x^2 I_2^2 R_{02} = \omega_i'$$

Variable LOSS = Constant LOSS

$\omega_i' = x^2 I_2^2 R_{02}$ is Invalid Statement

Ex $\omega_c = 500\ \omega$; $\omega_i' = 600\ \omega$; ω_T @ Max efficiency ?

Max η occurs when variable loss = Constant Loss

$\omega_c = \omega_i'$

$\omega_c = 600$

$\omega_T = 600 + 600 = 1200$; ✓

Constant LOSS = variable loss } Invalid

$\omega_i = \omega_c$

$\omega_i' = 500$

$\omega_T = 1000$

η_{max} occurs @ Loading $x = \sqrt{\frac{\omega_i'}{\omega_{cu}}}$

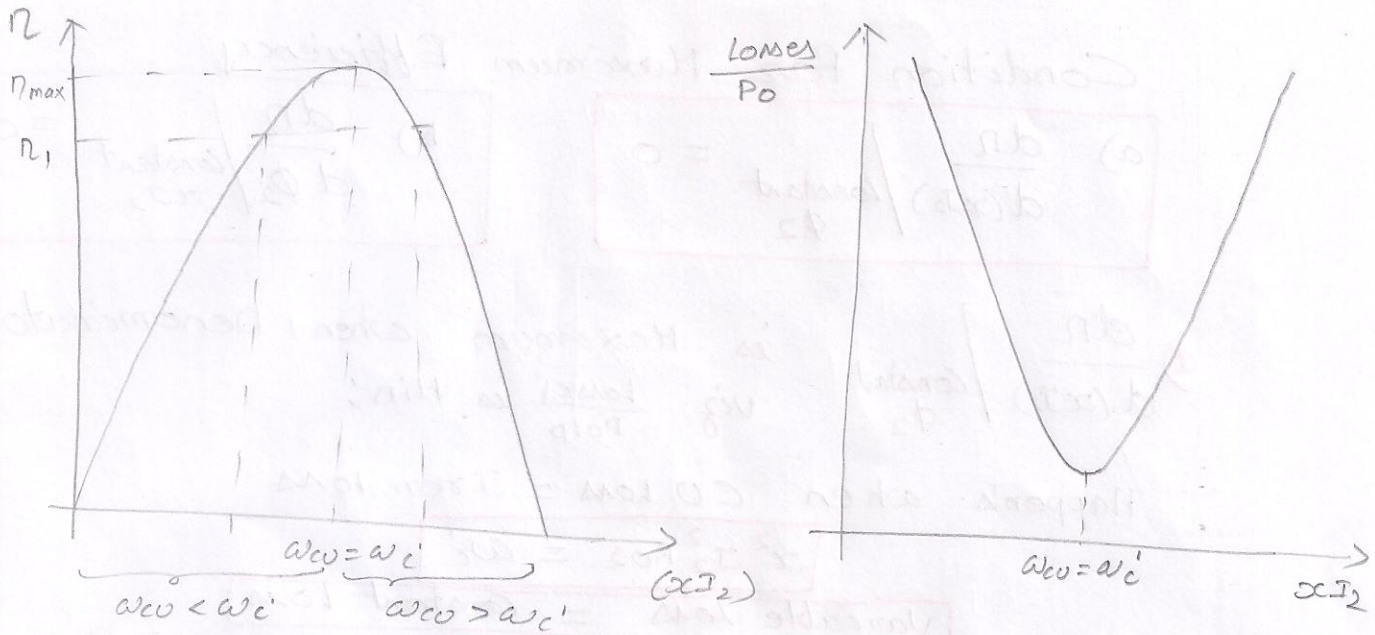
At η_{max} $x^2 I_2^2 R_{02} = P_c'$

$I_{2,m} = \sqrt{\frac{P_c'}{R_{02}}}$ where $I_{2,m} = xI_2$

$E_2 I_{2,m} = E_2 \sqrt{\frac{P_c'}{R_{02}}}$

$E_2 I_{2,m} = \frac{E_2 I_2}{I_2} \sqrt{\frac{P_c'}{R_{02}}} = E_2 I_2 \sqrt{\frac{P_c'}{I_2^2 R_{02}}}$

KVA of load at η_{max} = F.L KVA $\sqrt{\frac{P_i'}{F.L\ \text{cu loss}}}$



Efficiency curve w.r.t load current is double valued function so that same η is possible at two diff load conditions

b) $\left.\frac{d\eta}{d\phi_2}\right|_{\text{constant } (xI_2)}$ xI_2 is constant ω_{cu} is constant, ω_i is always constant

$\Rightarrow$ Losses are constant

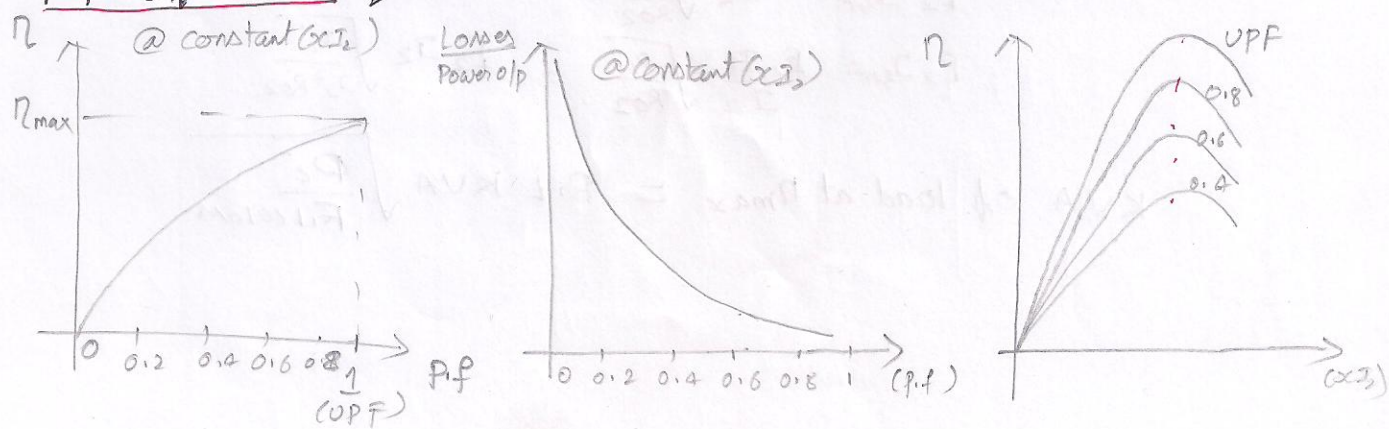
$$\eta = \frac{1}{1 + \frac{\text{Losses}}{P_{olp}}}$$

η_{max} — Dr min $\Rightarrow \left\{\frac{\text{Losses}}{P_{olp}}\right\}$ min

As Losses is constant P_{olp} must be max for Denominator to be minimum

$P_{olp} = E_2 (xI_2) \cos\phi_2$ is maximum at **U.P.f only**

Efficiency is same for lagging and leading P.f's and it depends on magnitude of P.f & is independent of P.f of load;



Procedure to find η from P.U losses

$$\eta_{F.L} = \frac{1 * \cos\phi_2}{1 * \cos\phi_2 + \omega_{co}(P.U) + \omega_i(P.U)}$$

$\omega_{co}(P.U)$ – P.U F.L Cu loss
$\omega_i(P.U)$ – P.U Iron loss

$$\eta_{x\ of\ FL} = \frac{x * \cos\phi_2}{x\cos\phi_2 + x^2\omega_{co}(P.U) + \omega_i(P.U)}$$

Ex $\%R = 2\%$, $\%X = 6\%$, $\%P_c = 1\%$

$\eta_{F.L}$ @ U.P.F, η_{max} @ ?, $\eta_{H.L}$ @ UPF

$$\eta_{F.L\ @\ U.P.F} = \frac{1 * 1}{1\times 1 + (1)^2 0.02 + 0.01} = 97.08\%$$

$$\eta_{H.L\ @\ U.P.F} = \frac{\frac{1}{2} * 1}{\frac{1}{2}\times 1 + \left(\frac{1}{2}\right)^2 0.02 + 0.01} = 97.08\%$$

Thus it shown η is double valued function;

$$x = \sqrt{\frac{\omega_i(P.U)}{\omega_{co}(P.U)}} = \sqrt{\frac{0.01}{0.02}} = 0.707;$$

η_{max} is achieved @ 0.707 loading @ UPF

$$\eta_{0.707\%\ of\ F.L\ @\ U.P.L} = \frac{0.707\times 1}{0.707\times 1 + 2(0.01)} = 97.24\%$$

(ω_i only)

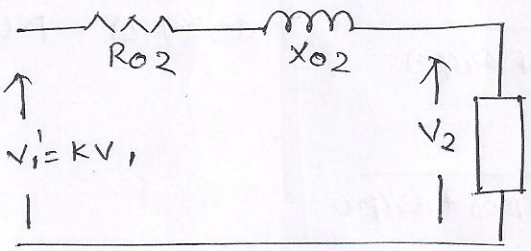
All Day Efficiency

$$\eta_{Allday} = \frac{O/P\ energy\ in\ KWH}{I/P\ energy\ in\ KWH} \Big/ 1\ Day$$

$\eta_{Allday} < \eta_{F.L\ Power}$

Refer Material for differences between Power Xmer & Distribution Xmer.

Voltage Regulation of Transformer



V_1' – N.L Secondary Terminal Voltage
V_2 – F.L Secondary Terminal Voltage

$$\% V.R = \frac{V_1' - V_2}{V_1'} \Rightarrow \text{Regulation Down}$$

Voltage Rating mentioned on Name plate of Xmer is No load voltage ⇒ Regulation is Regulation Down

$$\% V.R = \frac{V_1' - V_2}{V_2} \Rightarrow \text{Regulation Up}$$

Voltage Rating mentioned on Name plate of @ is Full load voltage ⇒ Regulation is Regulation Up

$$\% V.R = \frac{I_2 R_{o2} \cos\phi_2 \pm I_2 X_{o2} \sin\phi_2}{V_1'}$$

+ Lag
− Lead

$\Delta V = I_2 R_{o2} \cos\phi_2 - I_2 X_{o2} \sin\phi_2$ @ Lead

$I_2 X_{o2} \sin\phi_2$ componesates drop in $I_2 R_{o2} \cos\phi_2$

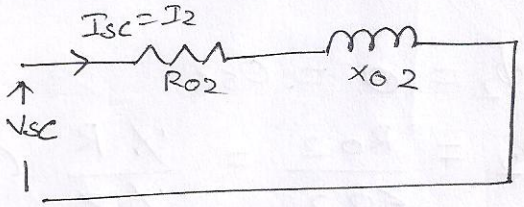
Under Compensation – Low Drop
Zero Compensation – Zero Drop
over Compensation – Rise Drop
} occurs at Lead p.f only

$$\% V.R = \frac{I_2 R_{o2}}{V_1'} \cos\phi_2 \pm \frac{I_2 X_{o2}}{V_1'} \sin\phi_2$$

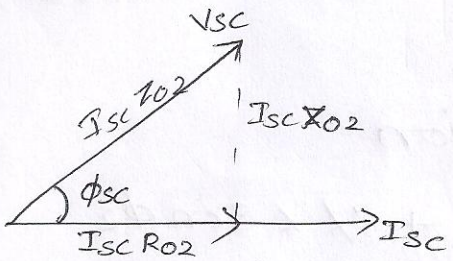
$$= (\text{P.U } 'R') \cos\phi_2 \pm (\text{P.U } 'X') \sin\phi_2$$

$$= (\%R) \cos\phi_2 \pm (\%X) \sin\phi_2$$

Under S.C condition,



$V_{SC} = I_{SC}(Z_{02})$



$I_2 R_{02} = I_2 Z_{02} \cos\phi_{SC}$

$I_2 X_{02} = I_2 Z_{02} \sin\phi_{SC}$

$$\% V.R = \frac{I_2 R_{02} \cos\phi_2 \pm I_2 X_{02} \sin\phi_2}{V_1'}$$

$$= \frac{I_2 Z_{02} \overset{\cos\phi_2}{\uparrow} \cos\phi_{SC} \pm I_2 Z_{02} \sin\phi_{SC} \sin\phi_2}{V_1'}$$

$$\% V.R = \frac{I_2 Z_{02} \cos(\phi_2 \mp \phi_{SC})}{V_1'} = \% Z \cos(\phi_2 \mp \phi_{SC})$$

$-$ → Lag $+$ → Lead;

Condition for Maximum Regulation

$$\% V.R = \% R \cos\phi_2 \pm \% X \sin\phi_2$$

Max. Reg. is achieved when R-Drop & X-Drop are additive; viz occurs @ Lag p.f

$$\phi_2 = \tan^{-1}\left(\frac{\% X}{\% R}\right) = \tan^{-1}\left(\frac{X_{02}}{R_{02}}\right) \text{(Lag)}$$

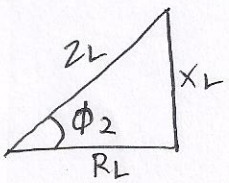
For R-L load

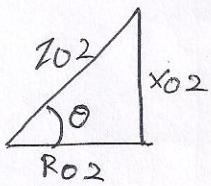
$\phi_2 = \tan^{-1}\left(\frac{X_L}{R_L}\right)$ Lag; $\Rightarrow$ $\frac{X_L}{R_L} = \frac{X_{02}}{R_{02}}$

If the ratio matches V.R is Maximum, V_2 is Minimum

θ_2 – Load angle of xmer

θ – Internal impedance angle of xmer

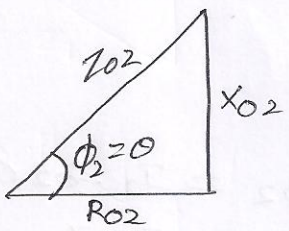




The two Δle's are identical at V.R max.

At Max. V.R

viz $\phi_2 = \theta = \theta_{sc}$



$$\cos\phi_2 = \frac{R_{02}}{Z_{02}} = \frac{\%R}{\%Z} \quad (\text{Lag})$$

Value At Max. Regulation

$$\%V.R = \%R\cos\phi_2 + \%X\sin\phi_2$$

$$\%V.R = \%R\left(\frac{R_{02}}{Z_{02}}\right) + \%X\left(\frac{X_{02}}{Z_{02}}\right)$$

$$\%V.R = \%R\left(\frac{\%R}{\%Z}\right) + \%X\left(\frac{\%X}{\%Z}\right)$$

$$\%V.R_{Max} = \frac{(\%R)^2 + (\%X)^2}{\%Z} = \frac{(\%Z)^2}{\%Z} = \%Z$$

Ex; During S.C Test 8% of voltage is required to produce S.C Rated curred; What is Max voltage Regulation;

$\Rightarrow \%Z = 8\%$

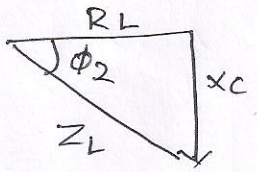
$\%V.R(max) = \%Z = \%8$,

Condition for Zero Regulation

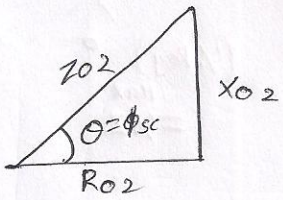
If R-Drop = X-Drop V.R = 0 this happens @ Lead p.f only;

$$\phi_2 = \tan^{-1}\left(\frac{R_{02}}{X_{02}}\right) \quad (\text{Lead})$$

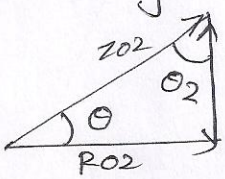
For R-C load



Impedance Δle of xmer



Resolting impedance Δle of xmer at Zero Regulat



$\theta + \phi_2 = 90°$

$$\frac{X_L}{R_L} = \frac{R_{02}}{X_{02}}$$

$$\% V.R = \% R \cos\phi_2 \pm \% X \sin\phi_2$$

$$\% V.R \text{ at } x \text{ of F.L} = x \left[\text{F.L V.R} \right] = x \left[\text{F.L V.R} \right]$$

$$\frac{x I_2 R_{02} \cos\phi_2 \pm x I_2 X_{02} \sin\phi_2}{V_2'}$$

% V.R at UPF = % R = % Full Load Cu. Loss

Ex If Internal impedance angle of xmer is $60° \rightarrow \theta$ at what ~~is~~ phase angle V.R max V.R zero occurs

Sol:- Condition for Max V.R

$$\phi_2 = \theta = 60°$$

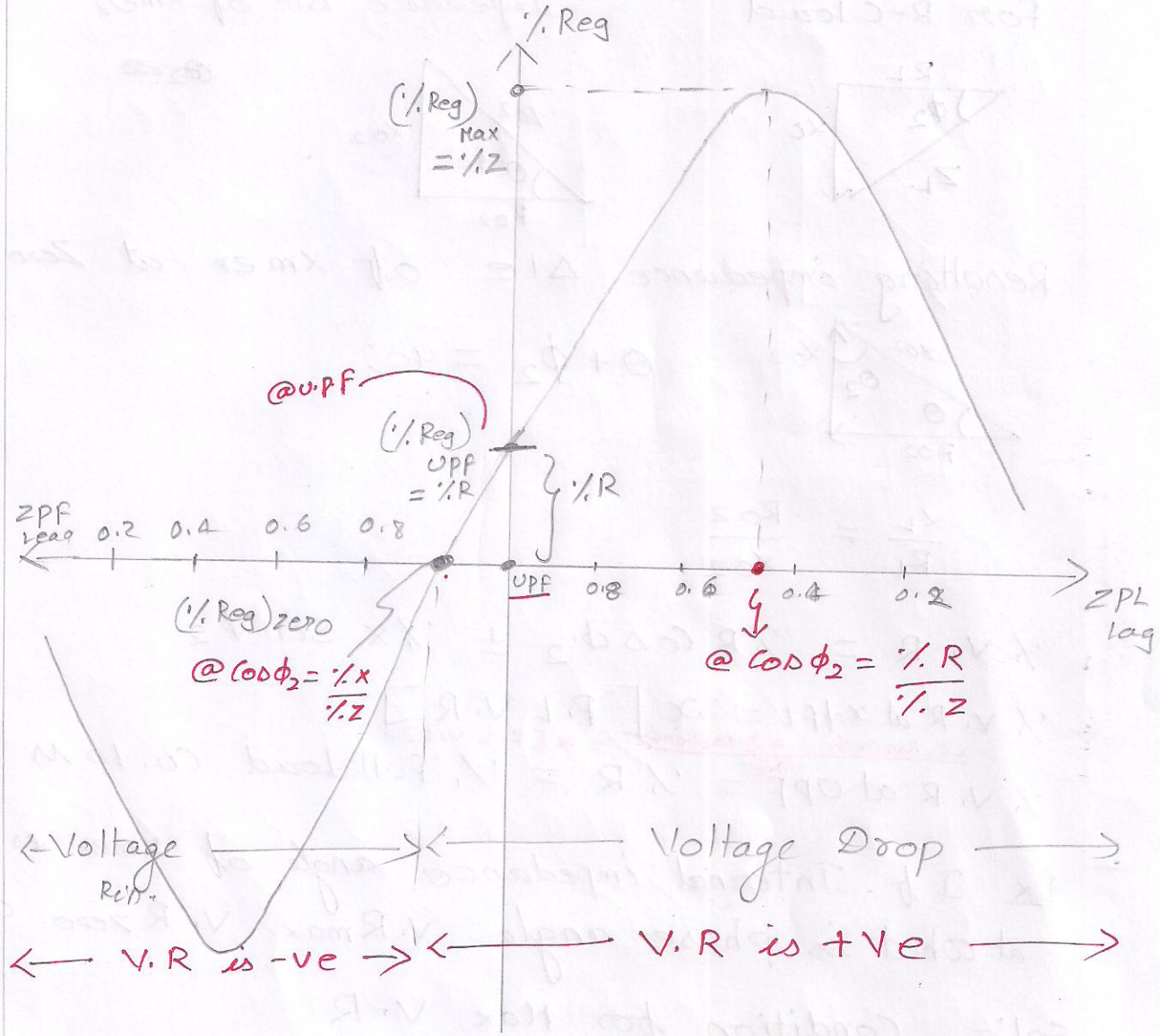
$$\cos\phi_2 = \cos 60 = 0.5 \text{ (Lag)}$$

Condition for Zero V.R

$$\phi_2 + \theta = 90$$

$$\phi_2 = 90 - 60 = 30° \text{ (Lead)}$$

$$\cos\phi_2 = 0.866 \text{ (Lead)}.$$

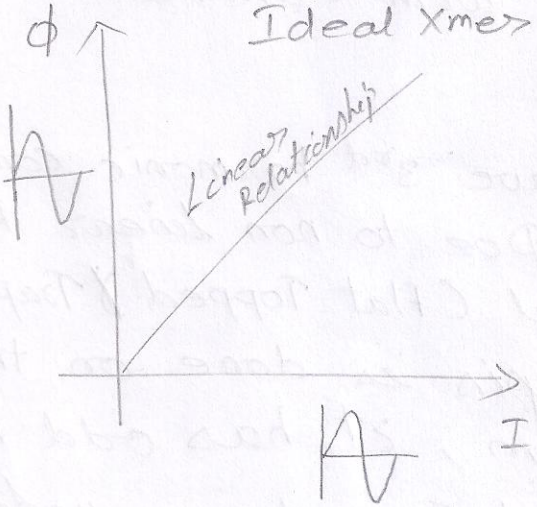

% Reg
(% Reg) Max = % Z
@ u.p.f
(% Reg) UPF = % R
% R
ZPF Lead
0.2
0.4
0.6
0.8
UPF
0.8
0.6
0.4
0.2
ZPL lag
(% Reg) zero
@ Cos ϕ2 = % X / % Z
@ Cos ϕ2 = % R / % Z
← Voltage Rise →
← Voltage Drop →
← V.R is -ve →
← V.R is +ve →

Effect of Non Linearities in Transformer Core

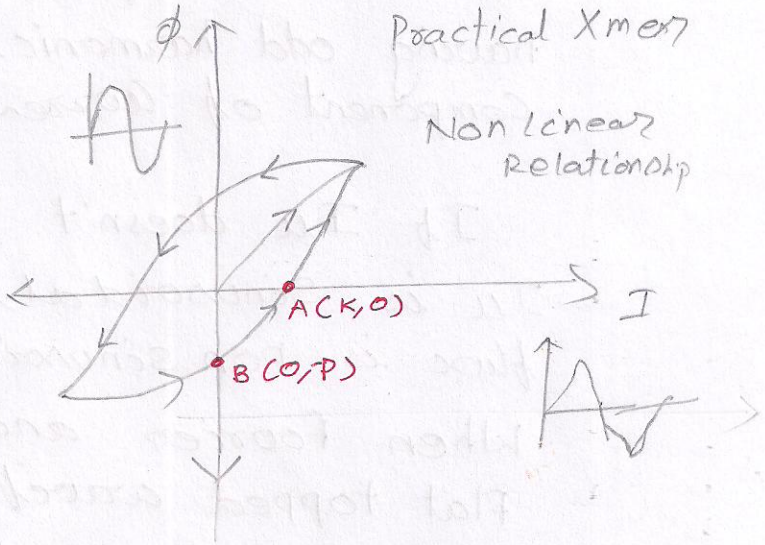
→ Saturation

→ Hysteresis

Ideal Xmer



Practical Xmer



→ Due to Non Linear Relationship I_M isn't Sinusoidal

→ Peakness of ϕ, I is achieved at Same Instant but

→ Current Zero point is advanced from flux Zero point by angle α_0 called Hysteresis angle of advance

→ Saturation of Core is due to peakiness

→ Hysteresis is due to α_0

→ If waveform is symmetrical about X-axis, Fourier Series has odd harmonics

→ If waveform isn't ~~Symets~~ Symmetrical about x-axis Fourier series has odd & even harmonics

→ I_M is symmetrical about X-axis it has odd harmonics along with fundamental. 3rd harmonic being dominant among them (40% - 50%) of total harmonic content.

Necessity of 3rd Harmonic Component

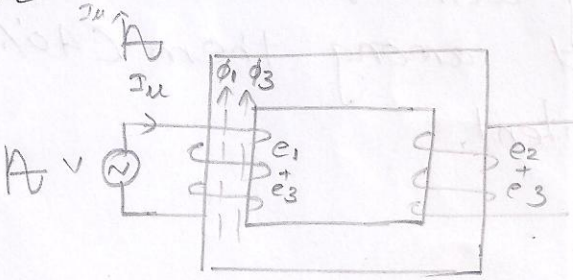
For sinusoidal Emf flux must be sinusoidal then the corresponding I_u must ~~have~~ be peaky having odd harmonics with dominant 3rd harmonic component of current

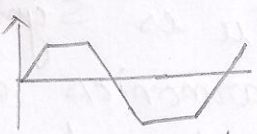
If I_u doesn't have 3rd harmonic component I_u is sinusoidal, Due to non linear Relationship flux is non sinusoidal (Flat Topped & Trapezoidal)
When Fourier analysis is done on this flat topped waveform, it has odd harmonics
The Flux being Flat Topped is undesirable
The Emf may contain fundamental & Third Harmonic Emf due to the components of flux

✡ Conclusion: I_u must contain 3rd harmonic current
✡ for sinusoidal flux, emf;

If source doesn't contain 3rd harmonic current the xmer must produce it internally.

Remark: If a sinusoidal voltage is applied to core, current flowing in it is sinusoidal (flat topped)
⇒ flux is Non sinusoidal having ϕ_1, ϕ_3, ϕ_5 ... etc. ϕ_3 being dominant, we concentrate more on operation of xmer with ϕ_1, ϕ_3.

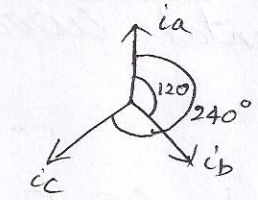




$\phi = \phi_1, \phi_3, \phi_5, \phi_7, \cdots$ odd harmonics

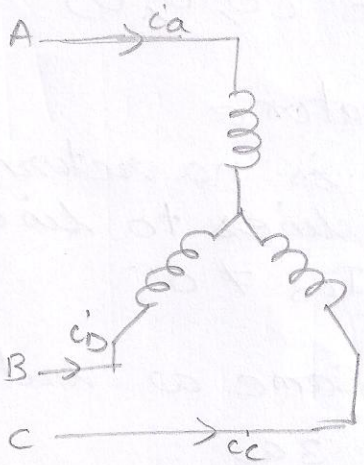
3-ϕ System

Fundamental currents are displaced by 120° Apart

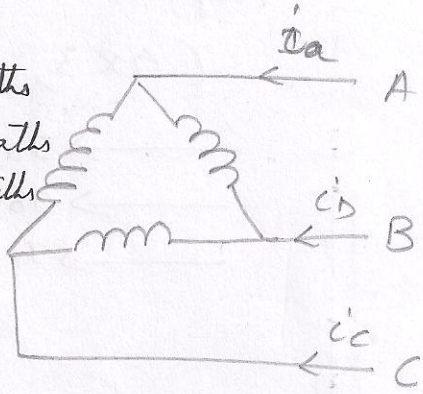


Basic property of 3-ϕ system is

$i_a + i_b + i_c = 0$;



i_a – B, C as Return Paths
i_b – A, C as Return Paths
i_c – A, B as Return Paths



Odd Harmonics are divided into two groups

a) 5, 7, 11, 13, --

$n = 3m \pm 1$

$m \rightarrow$ even integer

b) 3, 9, 15 -- (Triplen Harmonics)

$n = 3m$

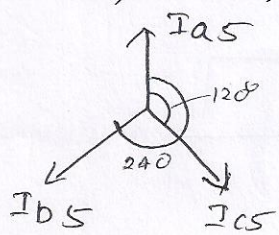
$m \rightarrow$ odd integers

Fundamental vectors Rotates at ω rad/sec

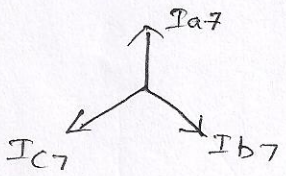
5th Harmonic vectors Rates at 5ω rad/sec

Displacement angles of 5th Harmonics

$(0 \times 5, 120 \times 5, 240 \times 5) = (0, 240, 120)$



opp phase Seq. to fundamental



Same sequence to fundamental

Displacement angles of 7th Harmonics

$(0 \times 7, 120 \times 7, 240 \times 7) = (0, 120, 240)$

At an instant I_{a5} passing opposite to I_{a7} with different frequencies so they cannot nullify each other

These harmonics can complete path from one line to other line like fundamental currents

Triplen Harmonics (3ω)

$(0\times 3,\ 120\times 3,\ 240\times 3) = (0, 0, 0)$

$\longrightarrow I_{a3}$
$\longrightarrow I_{b3}$
$\longrightarrow I_{c3}$

Cophasal in nature

There is no return path between lines to line

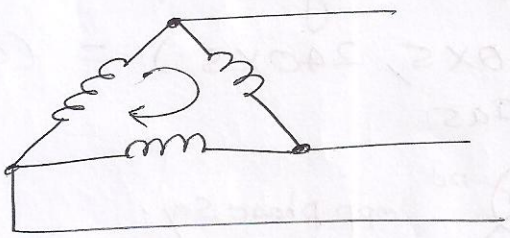
$I_{a3} + I_{b3} + I_{c3} \neq 0$;

Seq. components rotate at same ω but

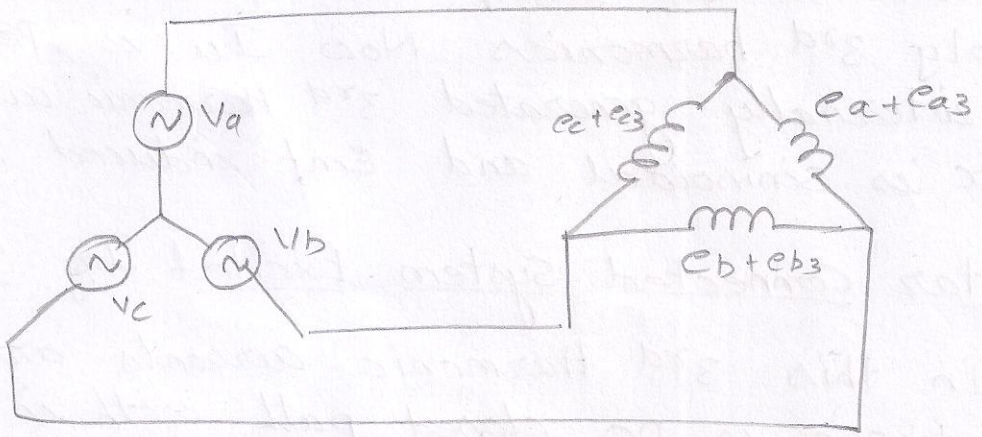
Triplen	Harmonics	at 3ω
5th	Harmonic	at 5ω
7th	Harmonic	at 7ω

A Y connected 3-ϕ system doesn't provide any closed path with in phases for flow of 3rd Harmonic current thats why shape of emf is Non-Sinusoidal I_{a3}, I_{b3}, I_{c3} doesn't Exist; Current is Sinusoidal
$\Rightarrow$ Flux is Flat Topped $\Rightarrow$ Emf is Non sinusoidal.

A Δ connected 3-ϕ system provides path in either phase $\therefore$ Emf is Sinusoidal; (Path doesn't exist in lines)



Δ Connected System Excited by Star Connected System



Applied voltage is Sinusoidal ⇒ I_M is Sinusoidal

∴ ϕ is Flat Topped / Trapezoidal with dominant 3rd Harmonic Component.

Core flux consists of fundamental flux & 3rd Harmonic flux.

∴ Emf is Non Sinusoidal having components $e_1 + e_3$ due to ϕ_1, ϕ_3 components.

→ fundamental emf's in xmer as balanced by Source voltages

→ Source doesn't have 3rd harmonic component voltages hence they cannot balance 3rd harmonic emf in xmer

→ These 3rd harmonic emf produce harmonic currents if there is closed path in phases.

→ In Δ we has path available and 3rd Harmonic currents which produce compensating flux

→ Compensating flux is in opposite direction to that of 3rd Harmonic flux to satisfy Lenz Laws.

$i_3 \rightarrow e_{a3}$ 90°; $e_{a3} \rightarrow \phi_{a3}$ 90° Total Phase Shift = 180°

Δ - Connected System is able to generate 3rd Harmonic current itself even if source doesn't supply 3rd harmonics. Now I_u is Peaky due to internally generated 3rd Harmonic current => flux is sinisoidal and Emf induced is Sinusoidal

Star Connected System Excited by Star System

In this 3rd Harmonic currents are n't castablid as there is no closed path with in phases Thus I_u has fundamental only Component Only ϕ, ε are Non sinusoidal.

Neutral Grounding method

If Xmer Neutral and source neutral are Grounded there exists a path with in phases for 3rd harmonic current;

∴ ϕ, ε are sinusoidal.

Single Phase Xmer

It doesn't have closed phath with in phase as there is only one phase

A closed path is sufficient ⇒ ϕ, ε are Sinusoidal

Requirements

a) 3rd Harmonic Currents should be available on single side (or) Both Sides of Xmer.

Shape of Emf in 1-ϕ Xmer is sinusoiddl under load

b) Magnitude of 3rd Harmonic impedance must be Low

If Z_3 is high I_3 is weak Compensating flux cannot nollify 3rd harmonic flux;

* Neutral grounding doesn't provide sinusoidal waveform(e) as 3rd Harmonic currents have to pass 100 km's of Length $Z \uparrow; I \downarrow; \phi_c \downarrow$;

Transcients : Fast & Sharp variation in electrical Quantities under distorbance

Switching Transcients : Transient in system when switch is opened(or) closed

Lightning Transcients : Transient due to Lightning Stroke

Switching Transcients are severe when switch is close at at @ which $V_i = 0$

~~Switching Transient~~ d
It's better to close the switch whe V_i reaches V_{max} at this point switching transients are absent

The instant at the switching takes place is beyond our control, so xmer should be designed to withstands these effects.

Doubling Effect

If switch is closed at Zero point of V_i, flux demand is $-\phi_m$ due to inertia flux available at this instance is Zero;

It attains an amplitude of $2\phi_m$ when normal flux attains ϕ_m this is called doubling effect.

If switch is closed at $V_i = V_m$; Demand = 0 Due to inertia flux starts from '0'; No Doubling effect.

As we Read $2\phi_m$, the Emf's in primary & Secondary Read 2 (Rated voltage) for short durati.

Generally Transient Excits for 1 cycle

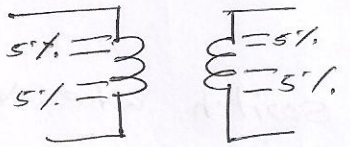
$$f = 50\,Hz$$

$$T = \frac{1}{50}$$

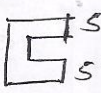
The Impulse / Surge emf are experiend for duration 1/50 sec

★ But Ckt $T = \frac{L}{R} > \frac{1}{50}$ Hence it stays for longer duration than $\frac{1}{50}$:

These voltages are experienced at 5% of end turn on both sides of windings of Xmer

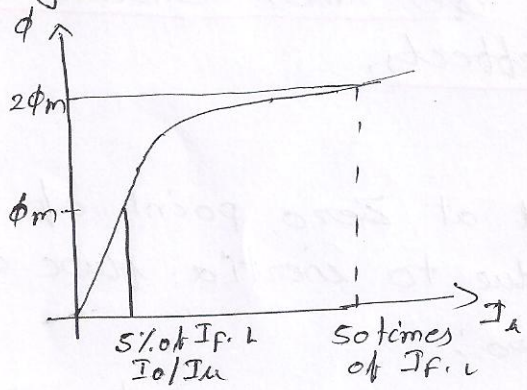


This may lead to ponctore of insulation.



To avoid it thickness of insulation is Increased

Magnetic Inrush Current



If $I_{f.l} = 1.0$ p.u

$I_{u\phi_m} = 0.05$ p.u

★ $I_{u,2\phi_m} = 50\,(0.05)$

$= 2.5$ p.u

This is called Magnetic Inrush current exists in primary only. (Transient Period)

Normal Operation $N_1 I_1 = N_2 I_2$ (I_o neglected)

$F_{Net} = 0$; Repulse forces Exist

Transient Operation $N_1 I_1 > N_2 I_2$

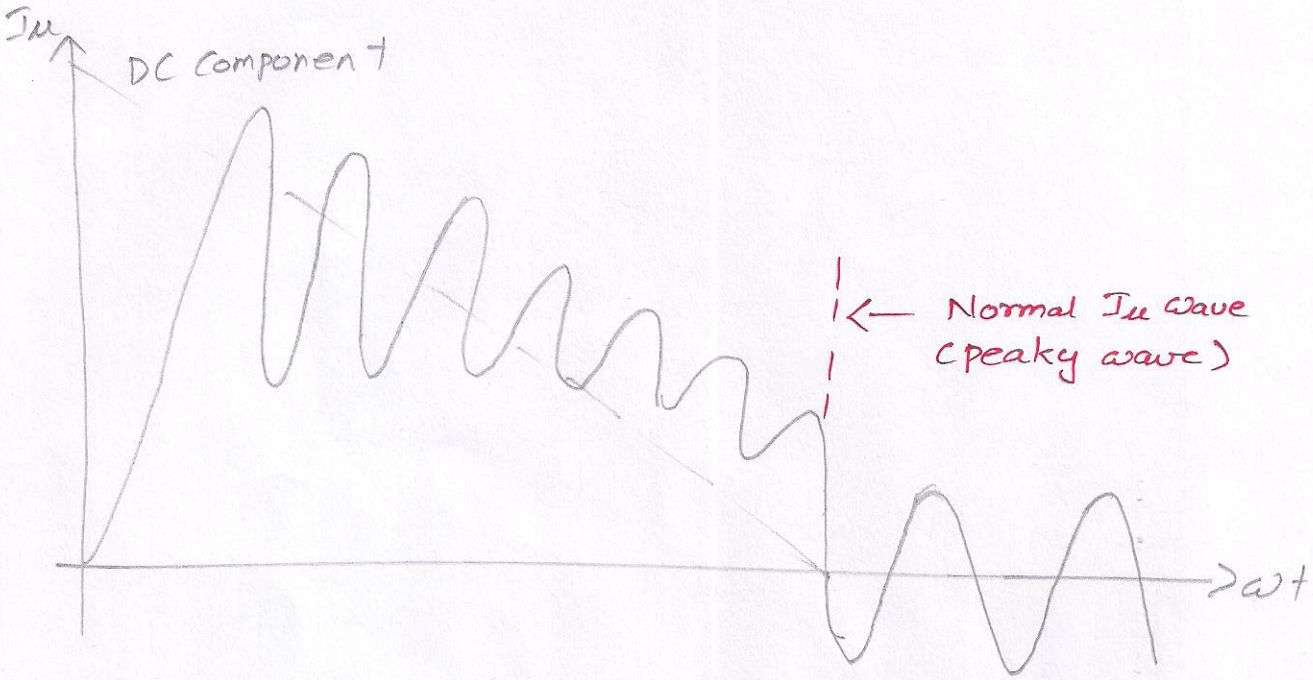
Both Repulsive & Axcias forces exist $F_{net} \neq 0$;

For every 1/2 cycle force directions are reverse to contain the vibrations / stress steel channels are placed in axcial direction.

$\phi_m \rightarrow$ Main field Flux due to I_u

Under normal operation $\phi_2 = \phi_1'$

Due to doubling effect $I_{u_{2\phi_m}} = 50\{I_{u,\phi_m}\}$



During Transient, ϕ is unidirection coz of strong DC component.

DC component suppresses -ve peaks

Its n't symmetrical about X-axis, due to DC compon

Fourier anylasis gives Iu has even & odd harmon during transient period

Now 2nd Harmonic is Dominant (Mag. Inrush Curr

In Normal Iu 3rd Harmonic is Dominant as it has only odd harmonics

This Transiet period is small and tripping isn't Required,

Generally Xmers Employ Differential Protection Scheme

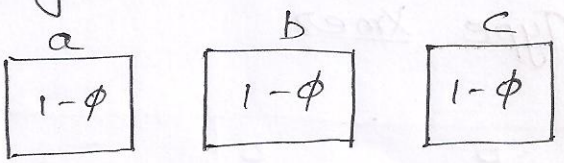
Second Harmonic Restraining Coil is Employed for unnecessary tripping due to magnetic Inrush current

When During Fault, 2nd harmonic Component is absent.

The Second Harmonic Restraining Coil Searches for 2nd harmonic Current. If it detects coil is energized and deenergization of Relay operating Coil Takes place thereby avoiding unnecessary tripping of Xmer.

Three Phase Transformers

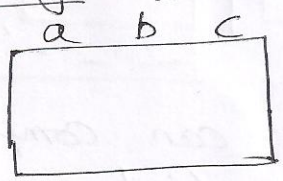
Realized Using Three Phase Bank Xmer & Single unit Xmer.



Phases are magnetically isolated and electrically connected in Y (or) Δ

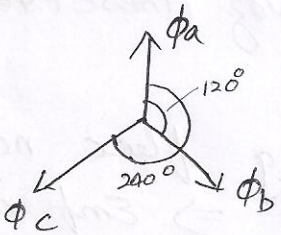
No interlinking

Single Unit 3-Ph Xmer



Phases are magnetically coupled and electrically connected in Y (or) Δ

In a 3-Ph Xmer, flux has 3-φ fundamental flux component and 3-φ third harmonic flux component



$\phi_a + \phi_b + \phi_c = 0$

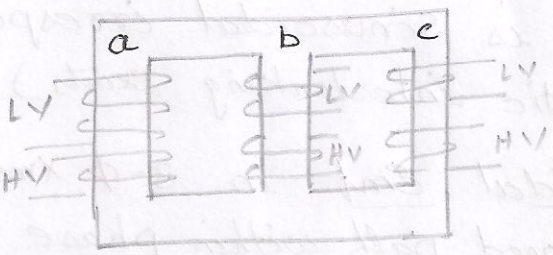
$\longrightarrow \phi_{a3}$

$\longrightarrow \phi_{b3}$

$\longrightarrow \phi_{c3}$

$\phi_{a3} + \phi_{b3} + \phi_{c3} \neq 0$;

3-Limbed Core Type Xmer

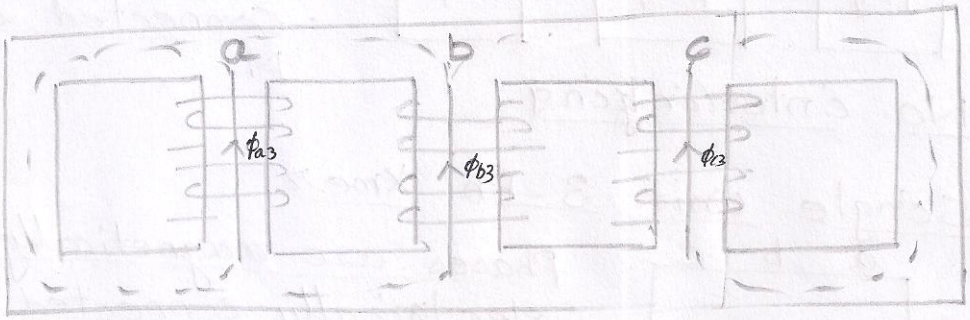


Fundamental flux component satisfies basic property of 3p-system so these fluxes can complete path from one ph. limb to another limb.

As 3rd-harmonic flux component are cophasal in nature they cannot traverse path from one limb to another. More over this flux cannot travel through air as $\mathcal{R} \Rightarrow$ high;

As it doesn't allow 3rd harmonic flux component (Due to interlinking nature) in the core and has only fundamental component of flux; Emf induced is always sinusoidal even for Δ (or) Y connection winding.

5-Limbed Shell Type Xmer



Fundament Component of flux can complete its path from one limb to another limb.

Also 3rd Harmonic component flux can complete it paths through outer limbs viz these (ϕ_{a3}, ϕ_{b3}, ϕ_{c3}) Exists in the core.

For Δ-winding; Compensating flux nullified 3rd Harmonic flux $\Rightarrow \phi_{Net} = \phi_f$ $\Rightarrow$ Emf is sinusoidal

For Y-winding: No compensating flux $\Rightarrow \phi_{Net} = \phi_f + \phi_3$
$\Rightarrow$ Emf is Non sinusoidal.

For 3-ϕ Bank Emf is sinusoidal irrespective of Δ (or) Y winding (Magnetic interlinking exists)

Condition for Sinusoidal Emf in 3-ϕ Xmer

→ There should be a closed path within phase for flow of 3rd Harmonic currents atleast on one side of 3-ϕ Xmer

→ ~~If~~ Else make the shape of emf in wdg sinusoidal in mag. ckt employed doesn't allow 3rd harmonic flux Just like 3-limbed core Type xmer.

Emf Equations in 3-ϕ Xmer

$$E_{1/ph} = 4.44\, N_{1/ph}\, B_m\, A_n\, f$$

$$E_{2/ph} = 4.44\, N_{2/ph}\, B_m\, A_n\, f$$

Once design is completed phase voltage is fixed and line voltages depends on type of connection

* Phase turn's ratio = $E_{1/ph} : E_{2/ph} = N_{1/ph} : N_{2/ph}$
* Line turn's Ratio = $V_{L-L(P)} : V_{L-L(S)}$
* Phase transformation Ratio = $\frac{1}{\text{phase Turns Ratio}}$
* Line transformation Ratio = $\frac{1}{\text{Line Turns Ratio}}$

Unless & otherwise specified turns Ratio means phase turns Ratio only.

Ex 220 KV / 132 KV Δ/Y Xmer phase turns Ratio?
→ Name plate gives Line turn's Ratio only

Sol:- Line turns Ratio = 220 : 132

Phase turns Ratio = $220 : \frac{132}{\sqrt{3}}$

Ex: If this Xmer is reconnected as Y/Δ, new voltage Rating of Xmer is

Phase turn's Ratio = $220 : \frac{132}{\sqrt{3}}$

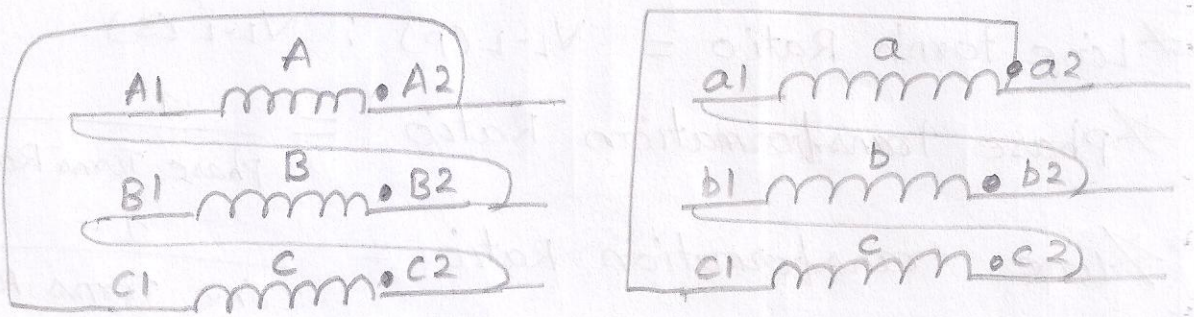
Line turn's Ratio = $220(\sqrt{3}) : \frac{132}{\sqrt{3}}$

Note: Default Values are L-L voltages & they are specified as turn's Ratio:

Different connections in 3-ϕ Xmer

a) Δ - Δ Connection

Note: A_2, B_2, C_2 are generally dotted terminals
Vector displacement between dot to dot is Zero
Vector displacement between dot to undotted is 180°



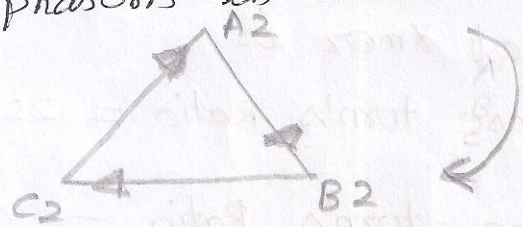
Step-1

$A \rightarrow A_2 - A_1 (B_2)$
$B \rightarrow B_2 - B_1 (C_2)$
$C \rightarrow C_2 - C_1 (A_2)$

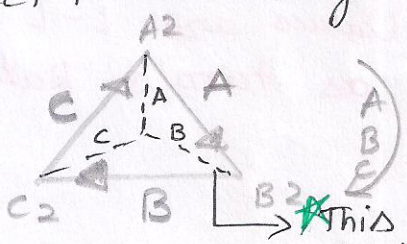
$a \rightarrow a_2 - a_1 (b_2)$
$b \rightarrow b_2 - b_1 (c_2)$
$c \rightarrow c_2 - c_1 (a_2)$

Step-2

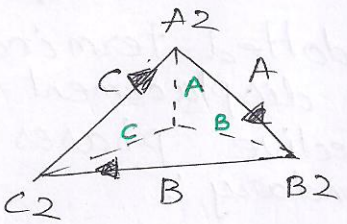
Vertex of Δle are out terminals of Primary
Always assume clockwise orientation and draw the phasors in same way (ckw)

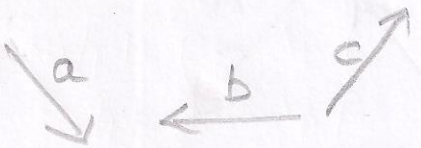


From step 1, we have wiring sequence; Now complete vect phasor diagram using data in step 1



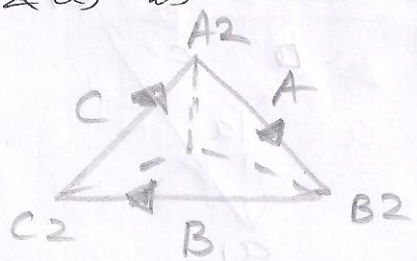
This helps in finding phase displacement between primary and secondary.

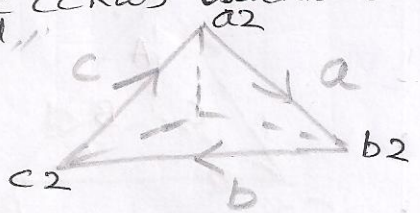




Step-3

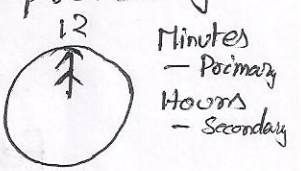
The out terminals of secondary are also dotted the displacement between primary & Secondary phases (A & a) is Zero degrees. Draw vector diagram. so that ABC (CKW) orientation is obtained.



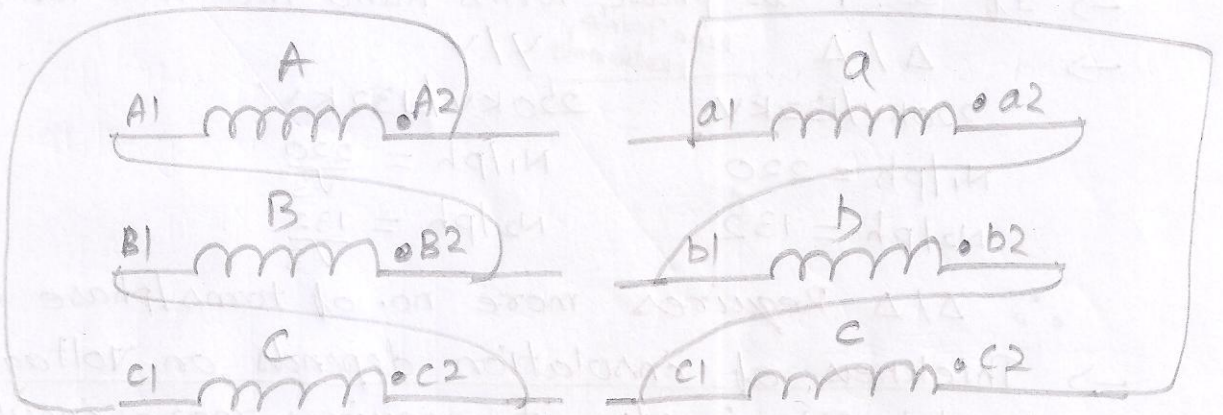


From step-1 we have wiring sequence of secondary use the information to complete phasor

Comparing phase Displacement between primary and secondary is 0°

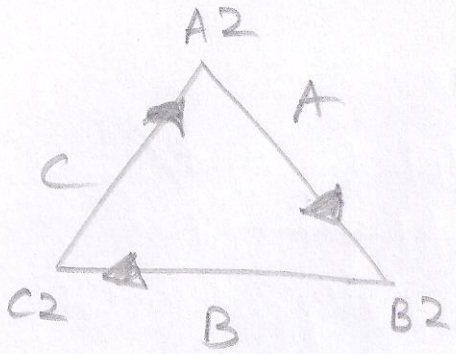


Dd0 (or) Dd12 Connections

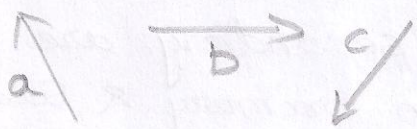


A → A2 – A1(B2)
B → B2 – B1(C2)
C → C2 – C1(A2)

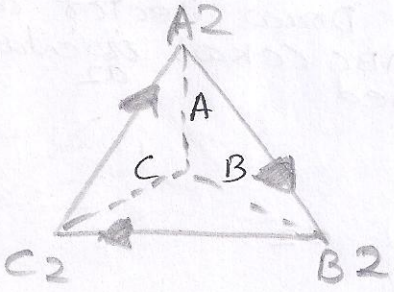
a → a1 – a2(b1)
b → b1 – b2(c1)
c → c1 – c2(a1)

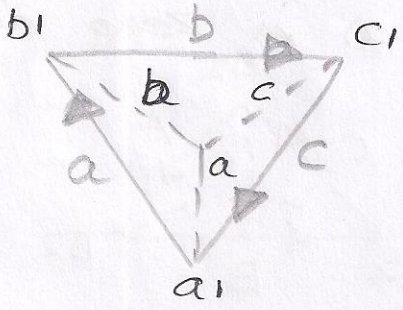


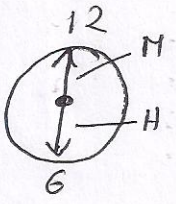
The out terminal of secondary is at undotted terminal $\Rightarrow$ vector displacement is 180° for respective phases of primary & secondary:



Now join them to form a Δ such that ABC in CKW is formed







180° Phase displacement between primary & secondary voltages;

$\Rightarrow$ Dd 6 Connection

Features

→ If $x:1$ is phase turn's Ratio the (line turn's Ratio $x:1$

→

Δ/Δ	(Line Turn's Ratio only) Y/Y
220kV/132kV	220kV/132kV
N_1/ph = 220	N_1/ph = $\frac{220}{\sqrt{3}}$
N_2/ph = 132	N_2/ph = $\frac{132}{\sqrt{3}}$

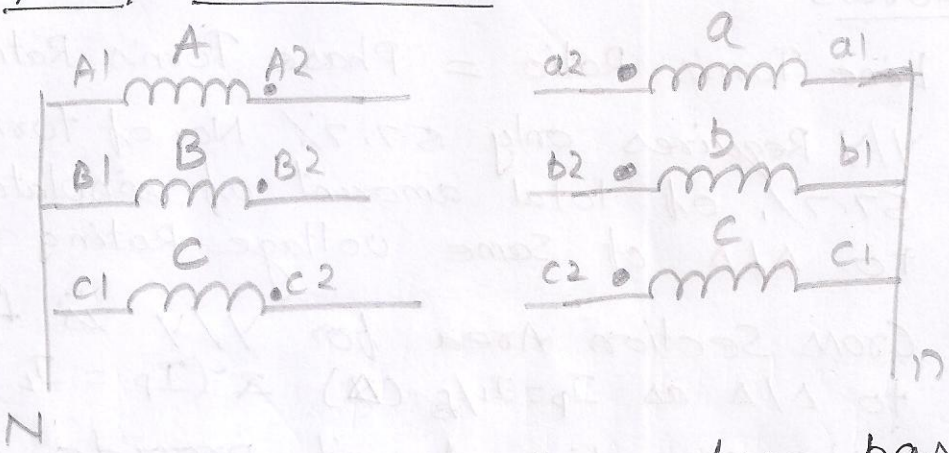
∴ Δ/Δ Requires more no. of turns/phase compared to Y/Y

→ Thickness of insulation depends on voltage (Phase)
As $V_{ph} = V_L$ in Δ/Δ, it requires more insulation compared to Y/Y

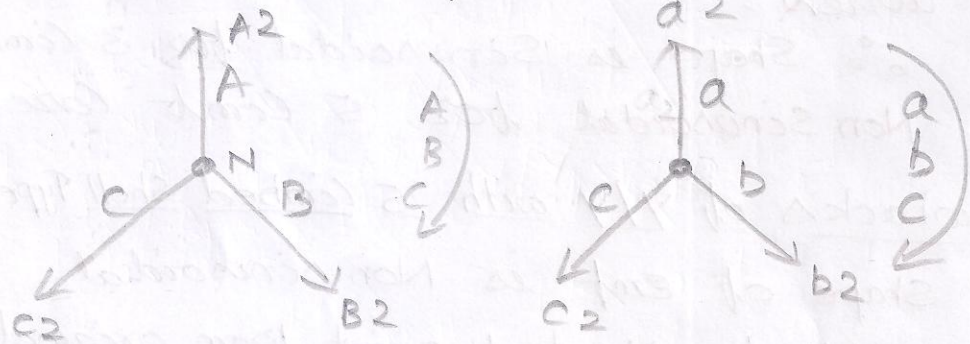
→ Conductor X-Area depends on phase current
$I_{ph} = \frac{I_L}{\sqrt{3}}$ (Δ/Δ), it requires 57.7% of Conductor when compared to Y/Y for same current Rating

→ Y/Y $\Rightarrow$ High voltage Low current Rating Xmer viz Small KVA
Δ/Δ $\Rightarrow$ Low voltage High current Rating Xmer viz Large KVA

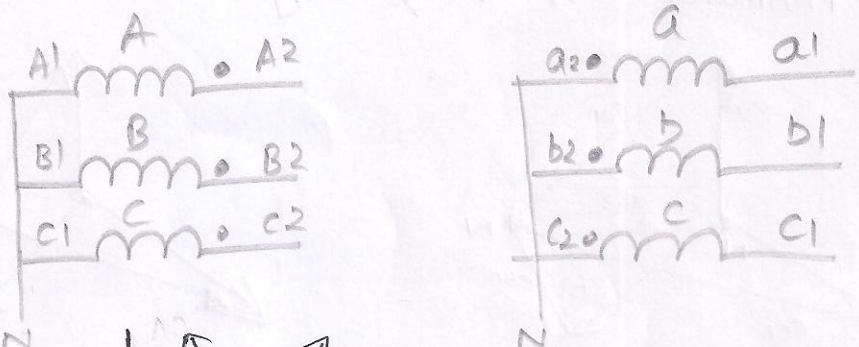
b) Y – Y Connection

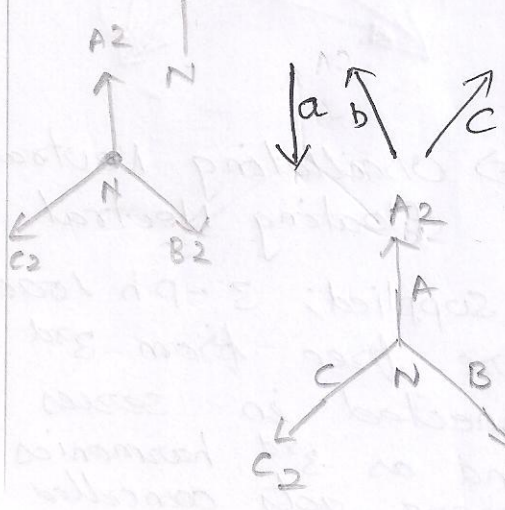


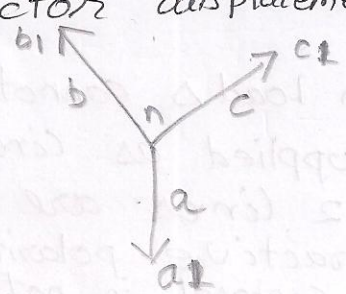
As both Primary & Secondary has dot at out terminals displacement (vector) = 0°;



Yy0 (or) Yy(12) Connection.







Primary has dotted & Secondary has ondotted terminals at output vector displacement is 180°

Y y 6 Connection

Features

→ Line Turn's Ratio = Phase Turn's Ratio

→ Y/Y Requires only 57.7% No. of turns/ph and 57.7% of total amount of insulation Compared to Δ/Δ of same voltage Rating

→ Cross Section Area for Y/Y is More/Less compares to Δ/Δ as $I_p = I_L/\sqrt{3}$ (Δ) & $(I_p = I_L)$ for (Y)

→ Y/Y Connection doesn't provide any closed Path within phases for flow of 3rd harmonic current;

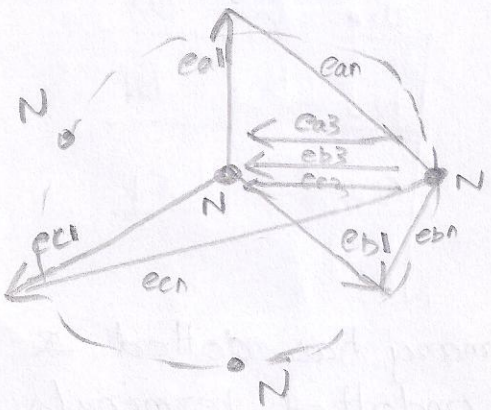
∴ Shape is Sinusoidal for 3 Limb Core Type & Non Sinusoidal for 5 Limb Core Type;

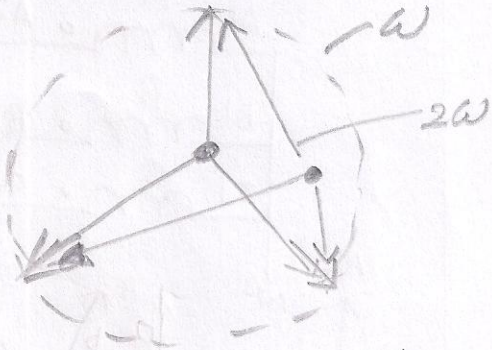
Drawbacks of Y/Y with 5 Limbed Shell Type (or) 3-ϕ Bank

→ Shape of emf is Non sinusoidal

→ Shift in Neutral point from original position due to 3rd Harmonic Emf's

→ Mismatch of frequency of vectors:





⇒ Oscillating Neutral / Floating Neutral.

→ 1-Ph Loads cannot be supplied; 3-ph loads can be supplied as Lines are free from 3rd harmonics as 2 lines are connected in series subtractive polarity and as 3rd harmonics voltage are cophased in nature there gets cancelled.

The above drawbacks in Y/Y transformer can be eliminated by providing closed path with in phases for flow of 3rd harmonic currents

i) Neutral Grounding

Z_3 is high @ $= R + jX_L = R + j(2\pi)(3fL)$

I_3 is Low $\Rightarrow$ Compensating flux is Low; so this cannot nullify 3rd harmonic flux component totally.

Therefore Neutral point is n't at original position but it slightly oscillates

ii) Tertiary Winding Method

Also Stabilizing winding is placed on core in Δ fashion.

There is closed path available in tertiary winding for flow of strong 3rd harmonic currents

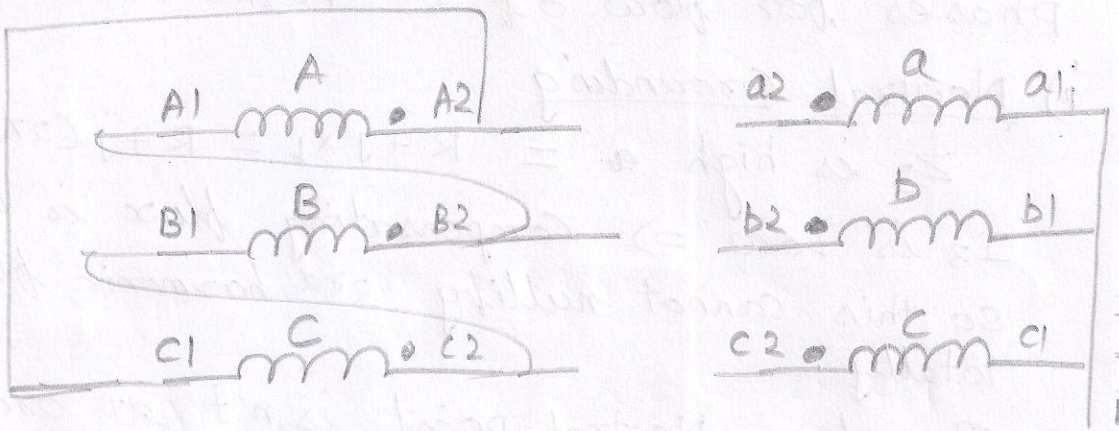
Z_3 is Low, I_3 is High $\Rightarrow$ Compensating flux is High Nullified 3rd Harmonic flux Component totally.

$\Rightarrow \phi_{Net} = \phi_f$; Emf is Sinusoidal;

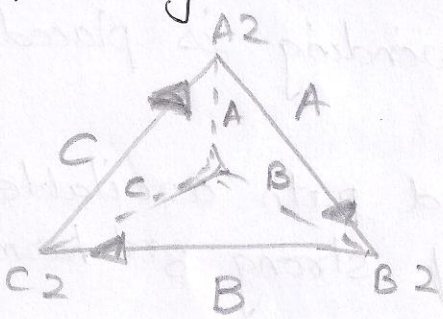
Now it can supply 1-ph & 3-ph loads as Neutral isn't shifted.

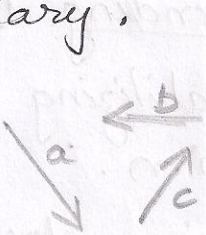
Reduces voltage unbalance due to 3rd Harmonic emf's from individual phases

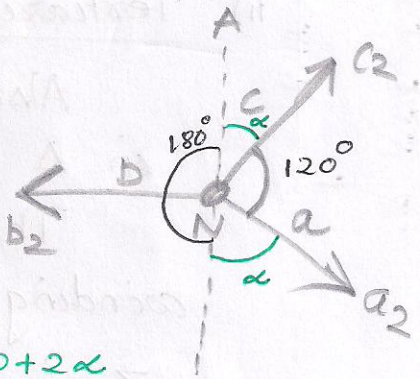
c) Δ/Y Connection



→ Dot terminals are similar viz vector phase displacement is Zero as we have dot to dot in Primary & Secondary.

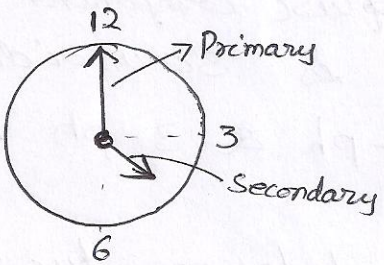






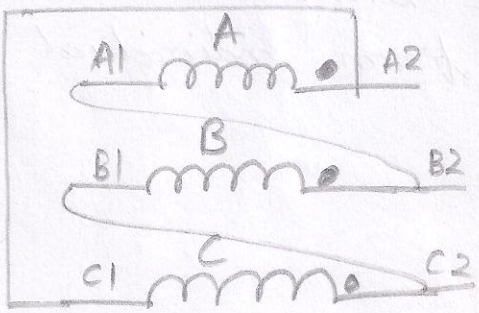
$180 = 120 + 2\alpha$

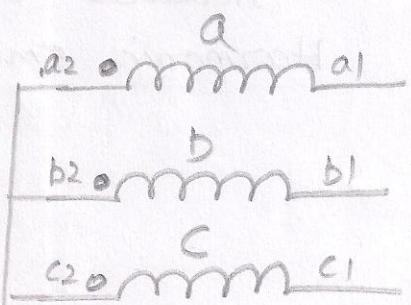
$\alpha = 30°$

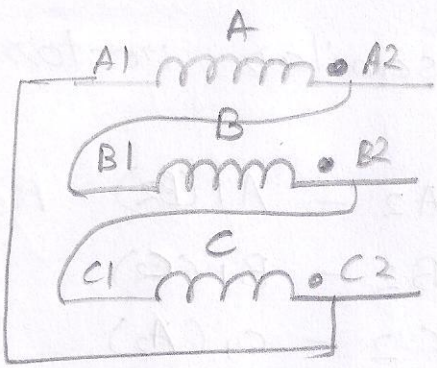


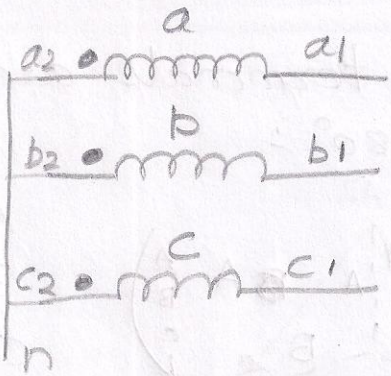
~~Dy~~ 150° between primary & Secondary phases of xmer

⇒ Dy5 Connection



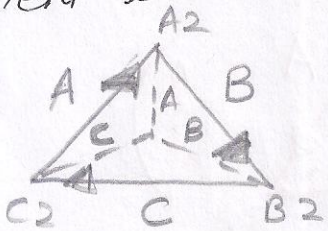


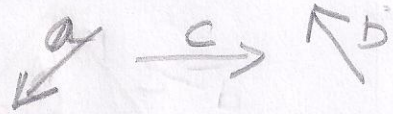


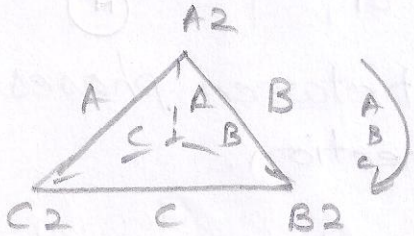


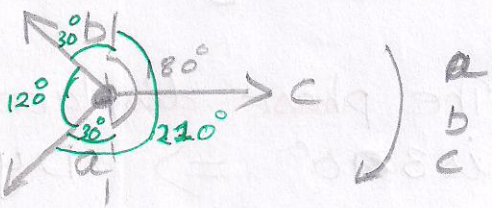
The out terminals are dotted & undotted, the vectored displacement is 180°

A → A2 – A1 (C2)
B → B2 – B1 (A2)
C → C2 – C1 (B2)









210° phase displacement between primary & secondary ⇒ Dy 7 Connection

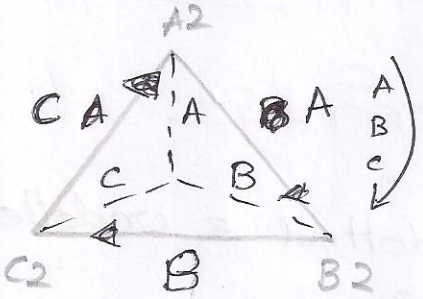
Analysis of all Transformer Connections

Transformation Ratio $x : 1$ Turn's Ratio $1 : x$

If V_1 is applied @ primary $\frac{V_1}{V_2} = \frac{1}{x} \Rightarrow V_2 = \frac{V_1}{x}$

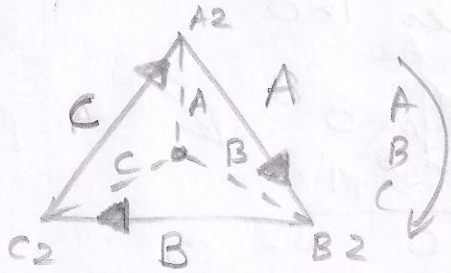
connection	Line Voltage	If $\frac{V_1}{x}$ is 100%	Voltage on Secondary
Δ – Δ	$V_1 : \frac{V_1}{x}$	100%	
Y – Y	$V_1 : \frac{V_1}{x}$	100%	
Δ – Y	$V_1 : \sqrt{3}\frac{V_1}{x}$	173%	⇒ 73% More
Y – Δ	$V_1 : \frac{V_1}{\sqrt{3}x}$	57%	⇒ 43% Less

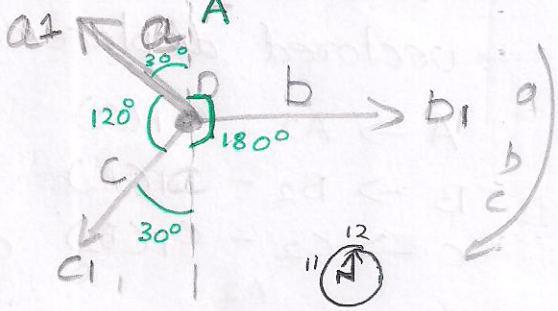
Out terminals are dissimilar vector displacemd is 180° :



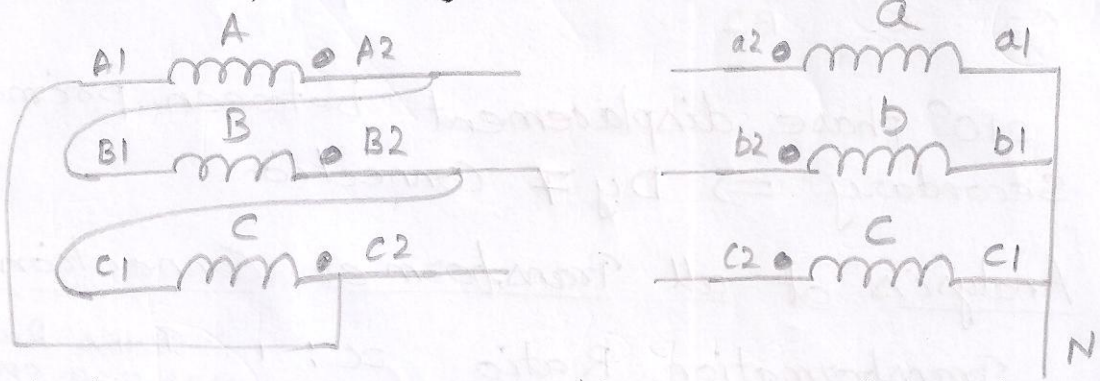
A → A2 – A1 (B2)
B → B2 – B1 (C2)
C → C2 – C1 (A2)

Now connect all individual secondary phases in 'y' such that abc (cook) is formed

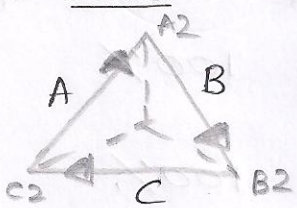




The phase displacement between phases (A & a) is 330° ⇒ Dy11 Connection.

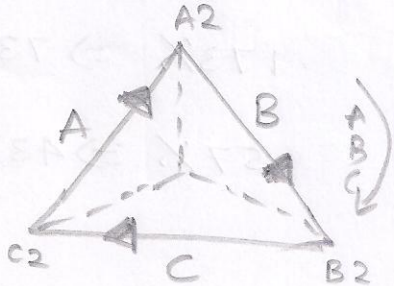


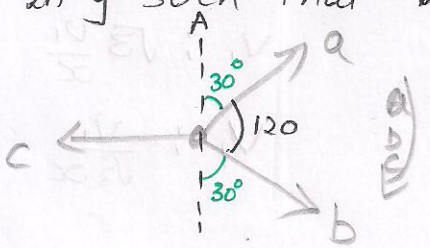
out terminals are dotted, vector phase displacemt is Zero.

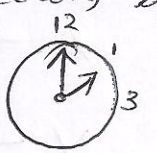


A → A2 – A1 (C2)
B → B2 – B1 (A2)
C → C2 – C1 (B2)

Now connect all individual phases of Secondary in 'y' such that abc (cook) is formed







Dy1

Features of Δ/Y

For $x:1$ transformation Ratio

$$\frac{V_{P,ph}}{V_{S,ph}} = \frac{x}{1}$$ If $V_{P,ph} = V_1$ then

$V_{S,ph} = \frac{V_{P,ph}}{x}$; Primary is Δ $\Rightarrow V_{P,L} = V_{P,ph} = V_1$

Secondary is Y $\Rightarrow V_{S,L} = \sqrt{3}\, V_{S,ph} = \sqrt{3}\frac{V_1}{x}$;

→ This offers highest secondary terminal voltage (73% more) among all xmer connection ⇒ Step up Applications.

→ For same voltage Rating, Δ-Y requires less no. of turns per phase among all the xmer connections, so that this xmer is most economical when compared to other connection

Reason: To under utilize 173% to 100%, No. of turns per phase are reduced.

→ As primary side Δ provides closed path for 3rd Harmonic current, 3rd Harmonic in individual Y phases on secondary side are absent so that neutral point on secondary side is maintained Stable and xmer can able to supply 1-ϕ & 3-ϕ loads. Ideal choice for distribution applications.

Drawback

$\phi_{compensating} = \phi_{3rd}$; The current (compensating) in Δ offers high impedance and mayn't nullify ϕ_3 due to non linearity totally.

If at all we need to maintain Low impedance No. of turns/ph must be decreased,

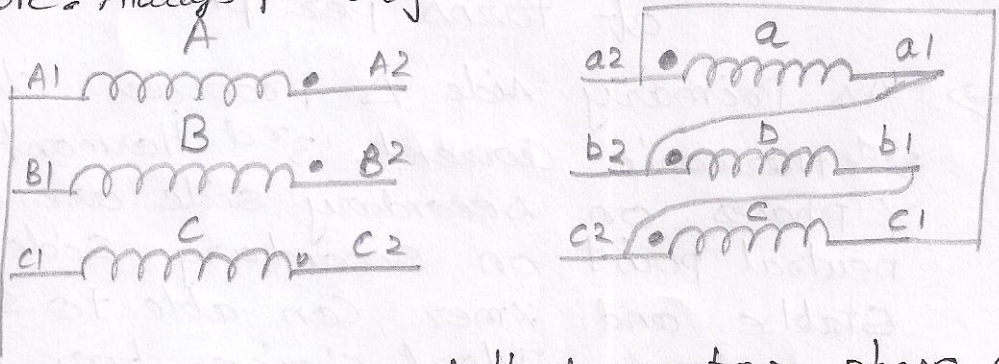
But Primary function of Xmer is to develop voltage.

Therefore nullification of 3rd harmonic flux due to non linearity isn't 100%. nullified, so a small amount of 3rd harmonic emf can be seen at secondary (Y) which oscillates the neutral point. (small shift) Load fluctuations may takes place for 1-Ph load.

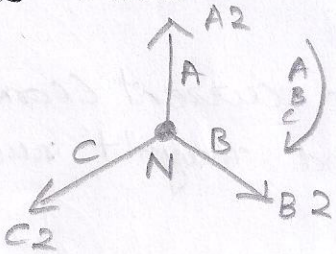
* Δ - Zig Zag connection will maintain balanced neutral

d) Y - Δ Connection

Note: Always primary side outcoming terminals are dotted terminals



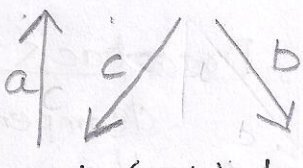
out terminals are dotted vector phase displacement is zero



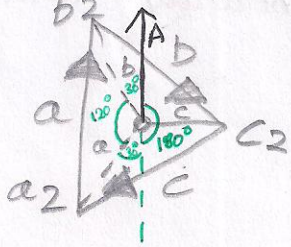
$a \rightarrow a_2 - a_1 (b_2)$

$b \rightarrow b_2 - b_1 (c_2)$

$c \rightarrow c_2 - c_1 (a_2)$

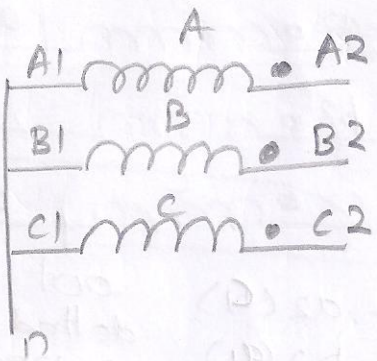


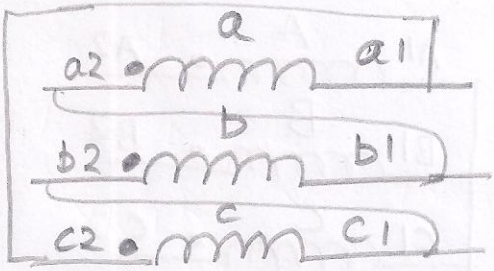
Now arrange them in (anti) to have abc



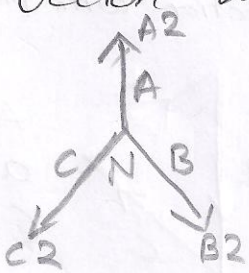
210° phase displacement between (A, a)

⇒ YD 7

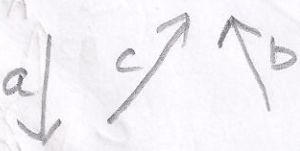




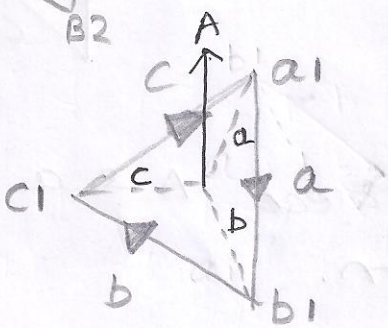
Out terminals are dotted & undotted ⇒ vector displacement 180°

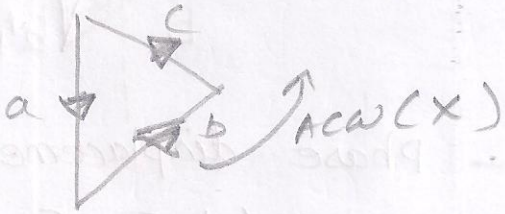


$a \rightarrow a_1 - a_2 (b_1)$
$b \rightarrow b_1 - b_2 (c_1)$
$c \rightarrow c_1 - c_2 (a_1)$

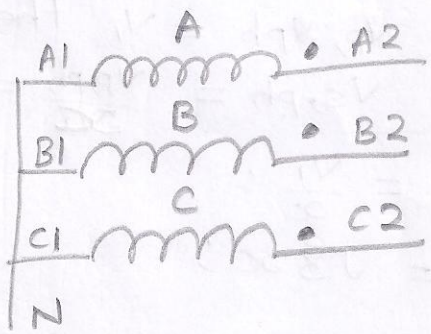


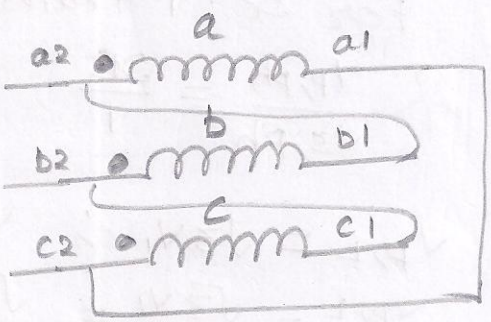
Now arrange phasors such that abc (ckw) is formed.

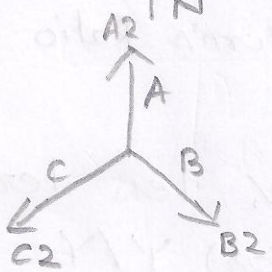




Phase displacement between primary & secondary is 30° ⇒ Yd 1 Connection.

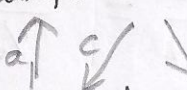






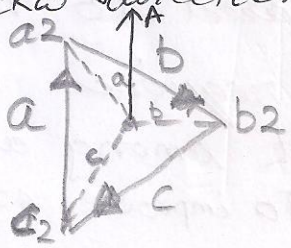
$a \rightarrow a_2 - a_1 (c_2)$
$b \rightarrow b_2 - b_1 (a_2)$
$c \rightarrow c_2 - c_1 (b_2)$

Out terminals are undotted on both sides vector displacement 0°



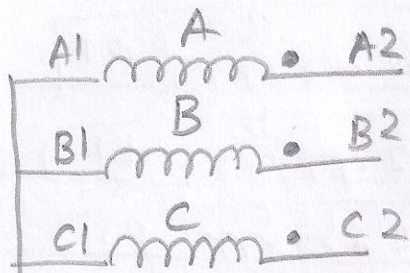
individual phasors in abc

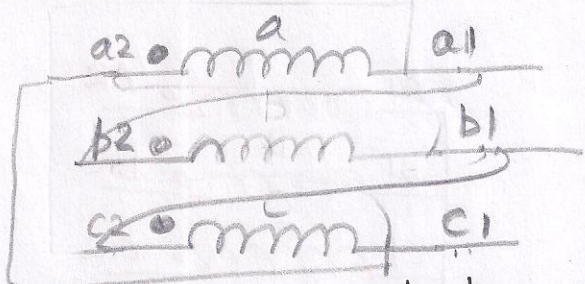
Arrange secondary ckw direction.

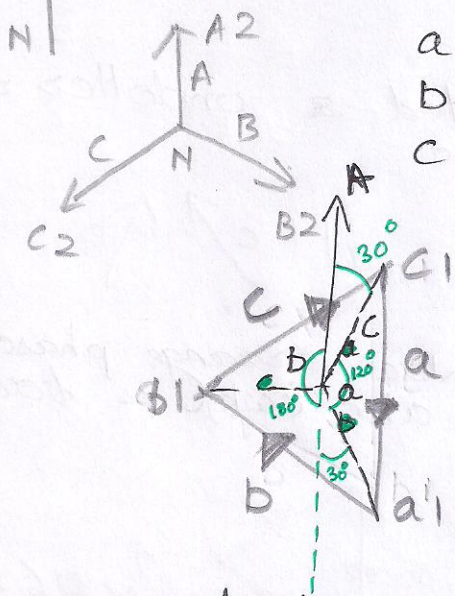


Phase displacement between A & a 30°

⇒ Yd 11



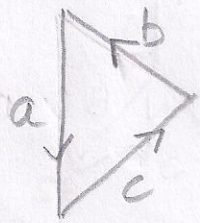




$a \rightarrow a_1 - a_2 \; (G_1)$
$b \rightarrow b_1 - b_2 \; (a_1)$
$c \rightarrow c_1 - c_2 \; (b_1)$

out termcinals are dotted & undotted $\Rightarrow$ vector displacement is 180°

Now arrange them in CKW direction with phase seq. abc



ACW
abc sequence
(Wrong)

Phase displacement between A & a is 150°

$\Rightarrow$ Yd 5 connection.

Features

For $x:1$ transformation Ratio;

$\frac{V_{P,ph}}{V_{S,ph}} = \frac{x}{1}$ If $V_{P,ph} = V_1$ then $V_{S,ph} = \frac{V_{P,ph}}{x} = \frac{V_1}{x}$;

$V_{P,L} = \sqrt{3} V_1$; $V_{S,L} = \frac{V_1}{x}$;

$\frac{V_{P,L}}{V_{S,L}} = \frac{\sqrt{3} V_1}{V_1/x} = \frac{\sqrt{3}}{1/x} = \sqrt{3} x$;

Line Turn's Ratio $x : \frac{1}{\sqrt{3}}$

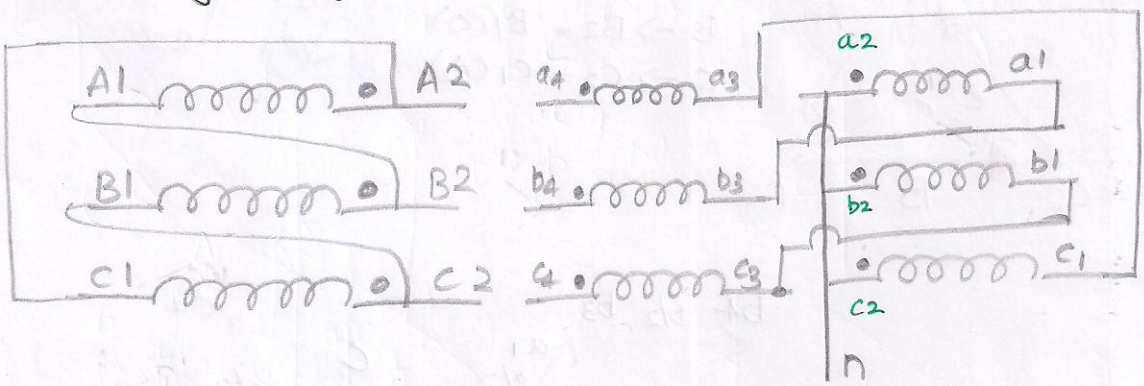
$\frac{V_{P,L}}{V_{S,L}} = \frac{x}{1/\sqrt{3}} = \sqrt{3} x$;

→ This connection produces 42.3% Less terminal voltage when compared to Δ/Δ (or) Y/Y

→ This connection requires highest no. of turns per phase on both among all connections for same voltage Rating (To improve 42.3% Less voltage to 100% More no. of turn's are req)

→ Economical to use this type for Step down app.
→ Not suitable for distribution coz Neutral is unavailable on secondary
→ As the Xmer secondary Δ provides closed path for 3rd Harmonic currents. Emf is Sinusoida

e) Δ - Zig Zag Y



It can be used in place of Δ/Y Xmer to get exactly stable neutral point

The Purpose of Zig Zag star is to nullify 3rd Harmonic emf in individual phases and each phase is divided into two parts (equals) The 3rd harmonic emf's are nullified due to series subtracting polarities of zig zag winding

** To get series subtractive polarity : undotted terminal is connected to undotted terminal (or) Dotted terminal is connected to dotted terminal to eliminate 3rd harmonic emf's in phases

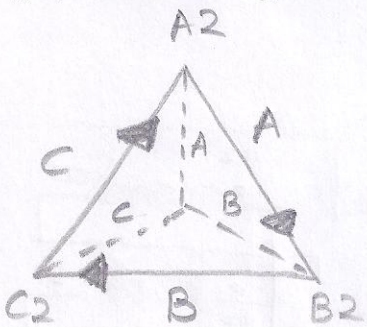
a → phase	$a_4 - a_3$	$- c_1 - c_2 (n)$
b → phase	$b_4 - b_3$	$- a_1 - a_2 (n)$
c → phase	$c_4 - c_3$	$- b_1 - b_2 (n)$
	1st Half	2nd Half

Consider ~~C-P~~ Ist half in a-phase $a_4 - a_3$

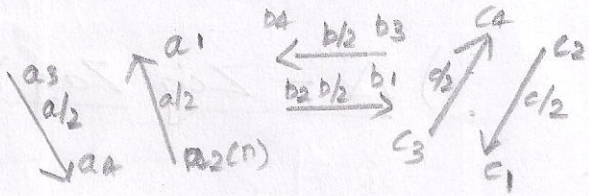
The out terminals are dotted (in (P) & (S)) ⇒ The vector displacement is 0

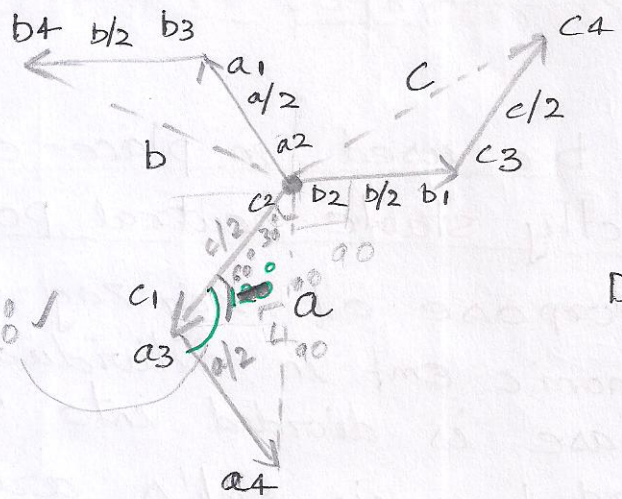
Consider IInd Half the $c_1 - c_2$ (n) ~~is connected~~

The out terminals of this section are dotted & undotted ⇒ vector displacement is 180°



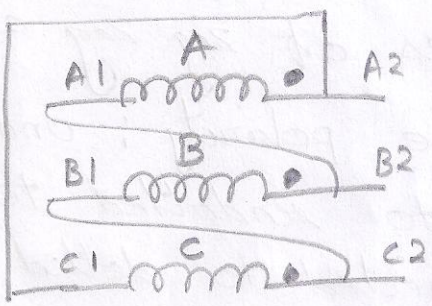
$A \rightarrow A_2 - A_1 (B_2)$
$B \rightarrow B_2 - B_1 (C_2)$
$C \rightarrow C_2 - C_1 (A_2)$

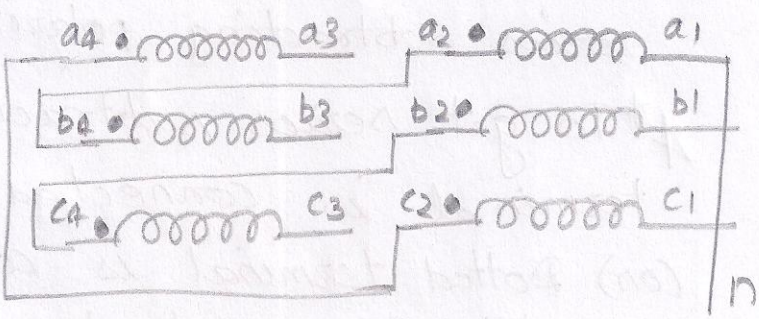


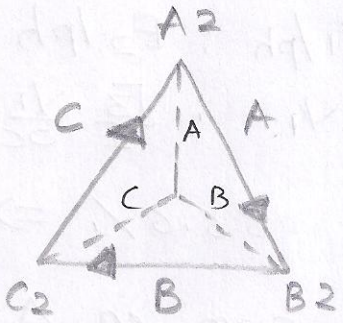


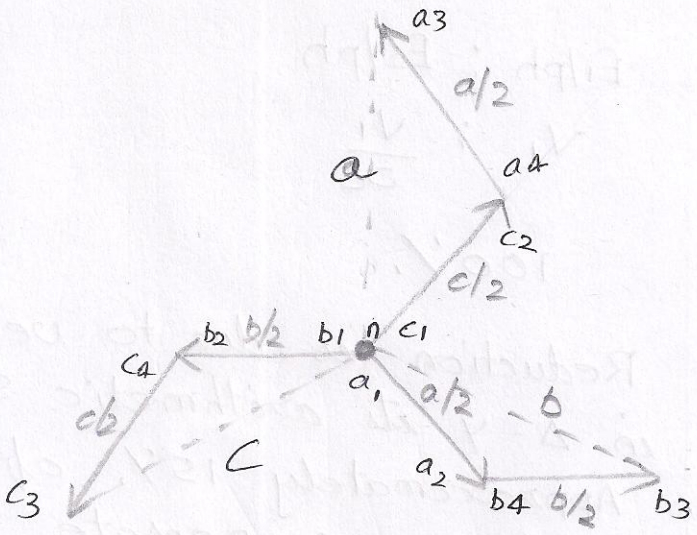
180° phase Displacement

DZG









Phase Displacement

Zero ⇒ D Z 12

Turns Ratio

i) Let phase ~~Transformation~~ is $x : 1$;

Phase voltage of primary $= V_1 =$ (line voltage of 'P'

$$\frac{V_{P,ph}}{V_{s,ph}} = \frac{x}{1} \Rightarrow V_{s,ph} = \frac{V_{P,ph}}{x} = \frac{V_1}{x}$$

Phase voltage across secondary half winding $\frac{V_1}{2x}$

$$V_{a3n}^2 = \left(\frac{V_1}{2x}\right)^2 + \left(\frac{V_1}{2x}\right)^2 + 2\left(\frac{V_1}{2x}\right)\left(\frac{V_1}{2x}\right)\cos 60$$

$$V_{a3n}^2 = \frac{3V_1^2}{4x^2} \Rightarrow V_{a3n} = \frac{\sqrt{3}V_1}{2x} \text{ (phase voltage)}$$

$$V_{a3b3} = \sqrt{3} \times \frac{\sqrt{3}V_1}{2x} = \frac{3V_1}{2x} \text{ (Line voltage)}$$

Line Transformation $V_1 : \frac{3V_1}{2x}$

$x : 1.5$

For $\Delta - Y$ $x : 1.732$

23.2% Less V_T is obtained when compared to Δ/y connection;

⇒ $\Delta - Z$ requires more no. of turn's per phase than Δ/y xmer for same voltage Rating.

(ii) $V_1 = V_{L,P}$

$V_{PH,P} = V_1$ (:D)

Δ – Y

E_1/ph : E_2/ph

V_1 : $\frac{V_1}{\sqrt{3}}$

100%.

Δ – Z

E_1/ph : E_2/ph

V_1 : $\frac{\sqrt{3}}{2}\frac{V_1}{\sqrt{3}}$

86.6% ⇒ 13.4% ↓

Reduction is due to vector sum in Δ – Z whereas in Δ – Y its arithmetic sum.

Approximately 15% of additional turns are used to compensate 13.4%, coz in Δ – Z its vector sum.

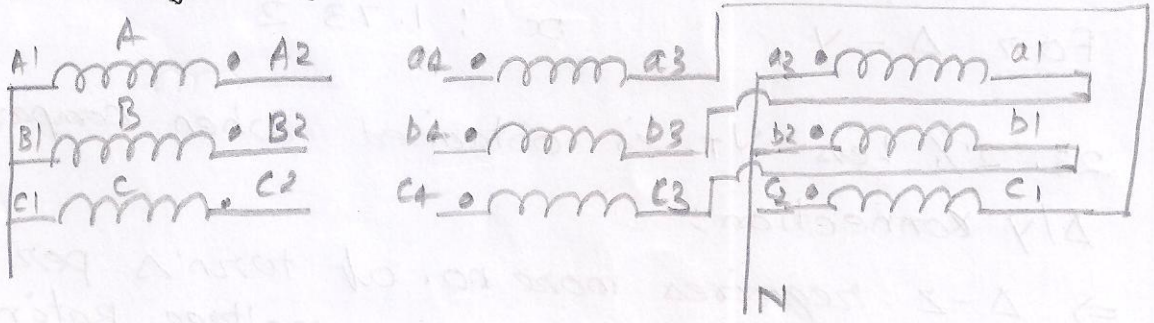
Note If 13.4% is taken the V_p is read < 13.4% coz V_p is vector sum so its taken little higher than 13.4%.

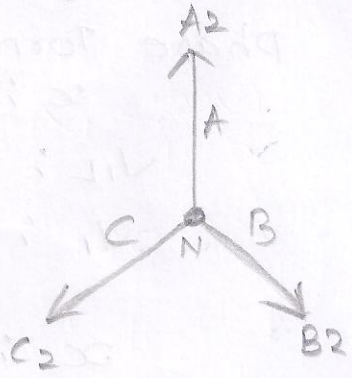
✡ Increasing no. of sections, higher order harmonics can be eliminated.

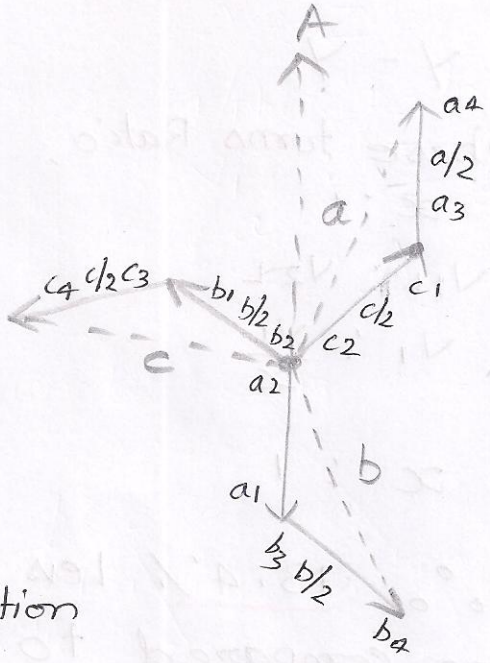
✡ 4 – sections till 5th order harmonics eliminated
8 – sections till 9th order harmonics eliminated

Due to series subtractive polarity, 3rd harmonics emf's gets cancelled in phases ⇒ phases are free from 3rd harmonic emf's ⇒ Neutral is stable;

f) Y – Zig Zag Y







Phase difference of
30 ⇒ Y - Z1 Connection

Possible phase shifts 180 ± 30, ± 30°;

If $x:1$ is phase turns Ratio

→ If V_1 is Line to line of primary

$\frac{V_1}{\sqrt{3}}$ is Phase Voltage of primary;

$$\frac{V_1}{\sqrt{3}} : V_S = x : 1 \Rightarrow \frac{\frac{V_1}{\sqrt{3}}}{V_S} = \frac{x}{1}$$

$V_S = \frac{V_1}{\sqrt{3}x}$; is phase voltage of secondary

In half section voltage available is $\frac{V_1}{2\sqrt{3}x}$

$$V_{a4n}^2 = \left(\frac{V_1}{2\sqrt{3}x}\right)^2 + \left(\frac{V_1}{2\sqrt{3}x}\right)^2 + 2\left(\frac{V_1}{2\sqrt{3}x}\right)^2 \cos 60$$

$$V_{a4n}^2 = \frac{V_1^2}{12x^2} + \frac{V_1^2}{12x^2} + \frac{V_1^2}{12x^2} = \frac{3V_1^2}{12x^2} = \frac{V_1^2}{4x^2}$$

$V_{a4n} = \frac{V_1}{2x}$; (phase voltage)

$V_{a4b4} = \frac{\sqrt{3}V_1}{2x}$ (Line voltage)

Line Turns Ratio $V_1 : \frac{\sqrt{3}V_1}{2x} \Rightarrow x : \frac{\sqrt{3}}{2} \Rightarrow x : 0.866$

Phase Turns Ratio $x : 1$

Y - Y

Phase turns Ratio

$x : 1$

$V_{1L} : V_{2L}$

$V_1 : \frac{V_1}{x}$

$x : 1$

Y - Zig Zag Y

Phase Turns Ratio

$x : 1$

$V_{1L} : V_{2L}$

$V_1 : \frac{\sqrt{3} V_1}{2x}$

$x : 0.866$

∴ 13.4% Less terminal voltage is obtained when compared to Y/Y connection.

Y - Y

$E_1/ph : E_2/ph$ (for V_1 Line voltage)

$\frac{V_1}{\sqrt{3}} : \frac{V_1}{\sqrt{3}x}$

57.7%

Y - Zig Zag Y

$E_1/ph : E_2/ph$

$\frac{V_1}{\sqrt{3}} : \frac{V_1}{2x}$

50%

change 7.7%

Approximately 9% of additional turns are required in Zig Zag

Phase voltage on secondary is Less in Y - Zig Zag Y compared to Y/Y since vector sum is ∠ Arithmetic Sum

For same voltage rating Y - Zig Zag Y requires more no. of turns per phase when compared to Y/Y

Due to series subtractive polarity ϕ_3 gets nullified and emf now is sinusoidal and neutral is stable

Advantages of Zig zag Y in Secondary

→ Shape of emf in ind. ph. is ~~AC~~ Sinusoidal

→ Maintains Neutral point at fundamental location

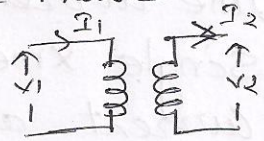
→ Maintains phase voltage constant

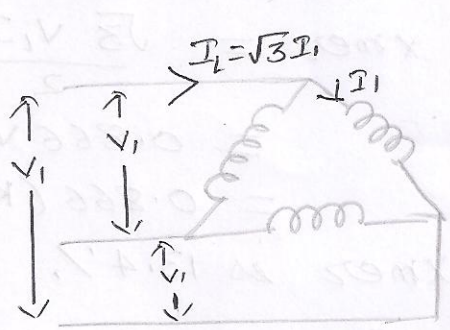
Neutral Grounding - Not preferred
Tertiary winding - cost ↑, Size ↑
Zig Zag Y - Effective, Economical

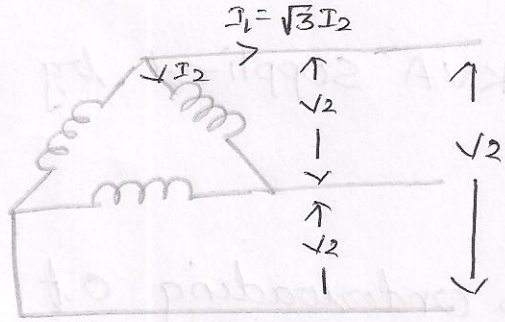
g) Open Delta Connection

Realized from three Single Phase Xmers

$(KVA)_{1-\phi} = V_1 I_1$ (or) $V_2 I_2$

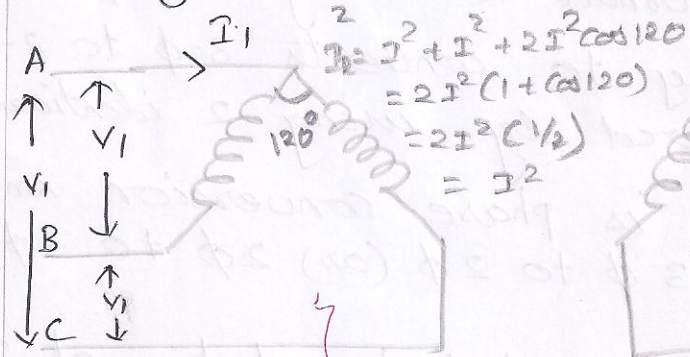


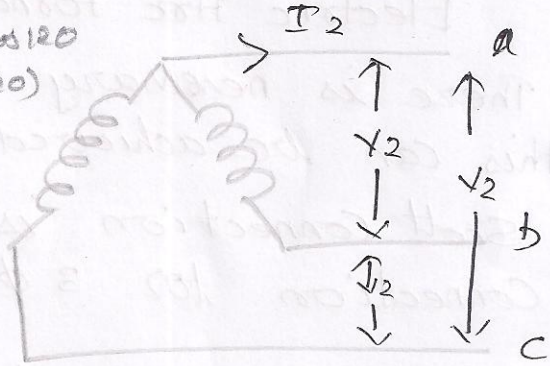




$$(KVA)_{\Delta-\Delta} = \sqrt{3} V_L I_L = \sqrt{3} (V_1)(\sqrt{3} I_1)$$
$$= 3 V_1 I_1 = 3 (KVA)_{1-\phi}$$

utilization factor of $\Delta-\Delta = 100\%$





For Safe Operation to avoid overloading

$V_L = V_1$; $I_L = I_1$ to limit damage of insulation and to limit overloading on each xmer (Design)

$$(KVA)_{3-\phi} = \sqrt{3} V_L I_L = \sqrt{3} V_1 I_1 = (KVA)_{V-V}$$

$$\frac{KVA_{V-V}}{KVA_{\Delta-\Delta}} = \frac{\sqrt{3} V_1 I_1}{3 V_1 I_1} = \frac{1}{\sqrt{3}} = 0.577$$

* Capacity of open delta is 57.7% capacity of closed delta without causing overloading.

If 100% load is maintained on open delta line current through B phase is $\sqrt{3} I_1$ then single xmer gets overloaded by 73% of F.L current and this will damage windings

KVA supplied by each xmer $= \frac{\sqrt{3} V_1 I_1}{2}$

$= 0.866 V_1 I_1$

$= 0.866 (KVA)_{1-\phi}$

$\Rightarrow$ underloading of each xmer is 13.4%.

utilization factor $= \frac{\sqrt{3} V_1 I_1}{2 V_1 I_1} = 0.866$

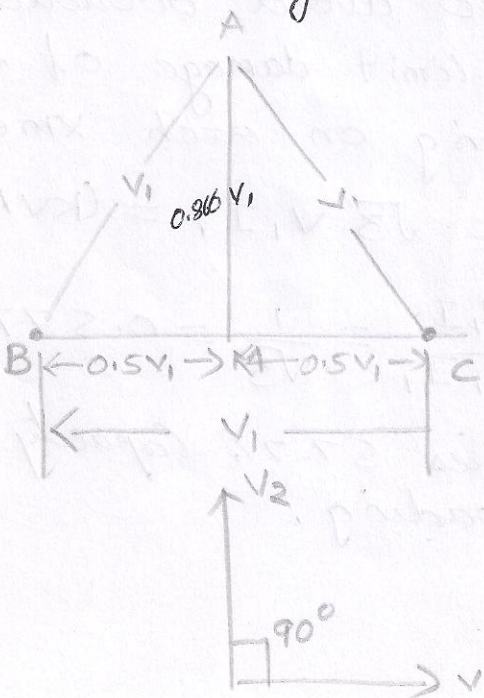
↳ 2 → 1-ϕ xmers are available

h) Scott Connection

Electric Arc Furnace & Welding M/c require 2-ph supply There is necessary to converts 3-ϕ to 2-ϕ & this can be achieved by using 2 identical xmers

Scott Connection is phase conversion xmer Connection for 3 ϕ to 2 ϕ (or) 2 ϕ to 3 ϕ

Vector Diagram behind implementation of Scott Connection



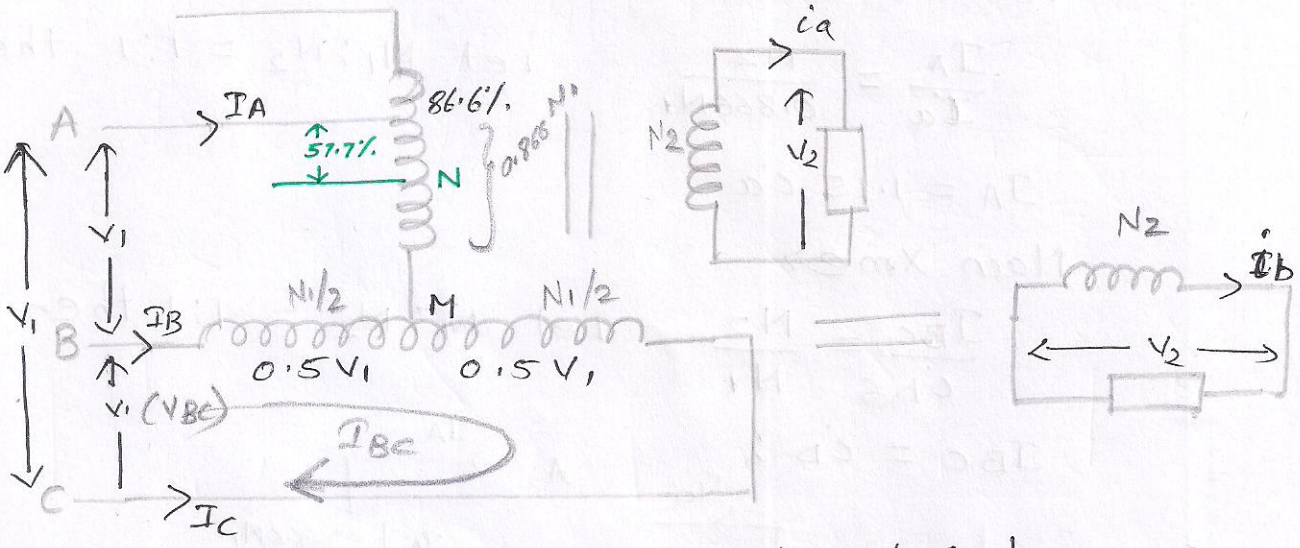
$V_{AB} = \left((0.5V_1)^2 + (0.866V_1)^2\right)^{1/2}$

$V_{AB} = V_1 = V_{AC}$

By using two vectors 3 phase system is achieved

If 3 ϕ supply is given 2 ϕ system can be achieved:

Xmer which has 100% turns in operation is Main Xmer
Xmer which has 86% turns in operation is Teaser Xmer



M isn't the Neutral point of 3ϕ System,

For getting Neutral point $V_{AN} = \frac{V_1}{\sqrt{3}} = 0.577 V_1$

Consider a point on teaser Xmer corresponding to voltage $0.577 V_1$ and mark as N.

$V_{AM} = 0.866 V_1$ $\quad V_{AN} = 0.577 V_1$

$V_{MN} = 0.289 V_1$

$V_{AN} : V_{MN} = 0.577 V_1 : 0.289 V_1 = 2 : 1$

$\Rightarrow$ Neutral point exists on Teaser Xmer neutral points divides the primary of teaser Xmer in Ratio 2:1

Location of Neutral pt from terminal A (top)

$$= 0.866 N_1 * \frac{2}{3}$$

Location of Neutral pt from terminal B (Bottom)

$$= 0.866 N * \frac{1}{3}$$

check whether neutral point is balanced or not

$$V_{CN} = \sqrt{(0.5V_1)^2 + (0.289V_1)^2} = 0.577 V_1$$

$\Rightarrow V_{AN} = V_{CN} = 0.577 V_1$, $\therefore$ Neutral is balanced and we can supply 1-ϕ Loads also.

Operation @ UPF

Teaser Xmer

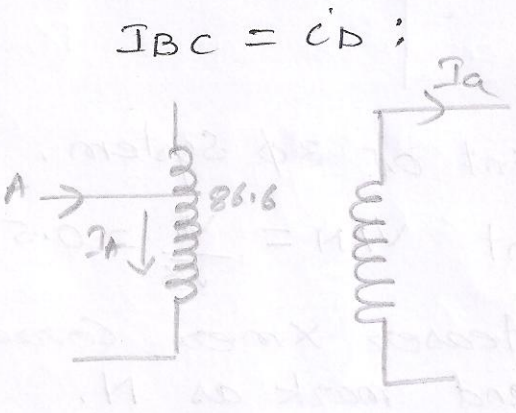
$$\frac{I_A}{I_a} = \frac{N_2}{0.866 N_1}$$ Let $N_1 : N_2 = 1:1$ then

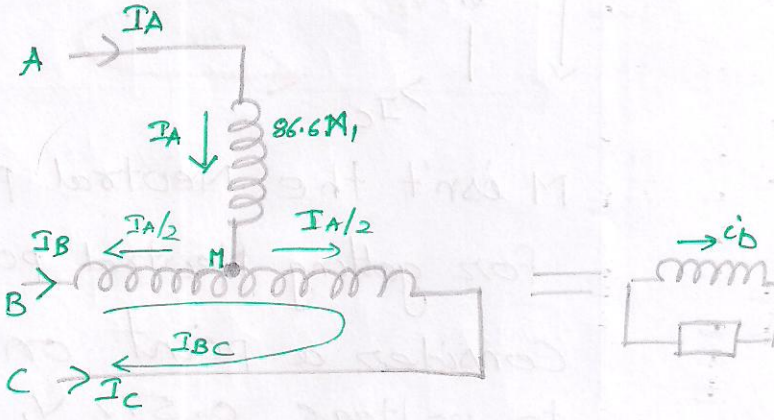
$$I_A = 1.15\, i_a$$

Main Xmer

$$\frac{I_{BC}\,P}{i_{D,S}} = \frac{N_2}{N_1}$$ Let $N_1 : N_2 = 1:1$ then

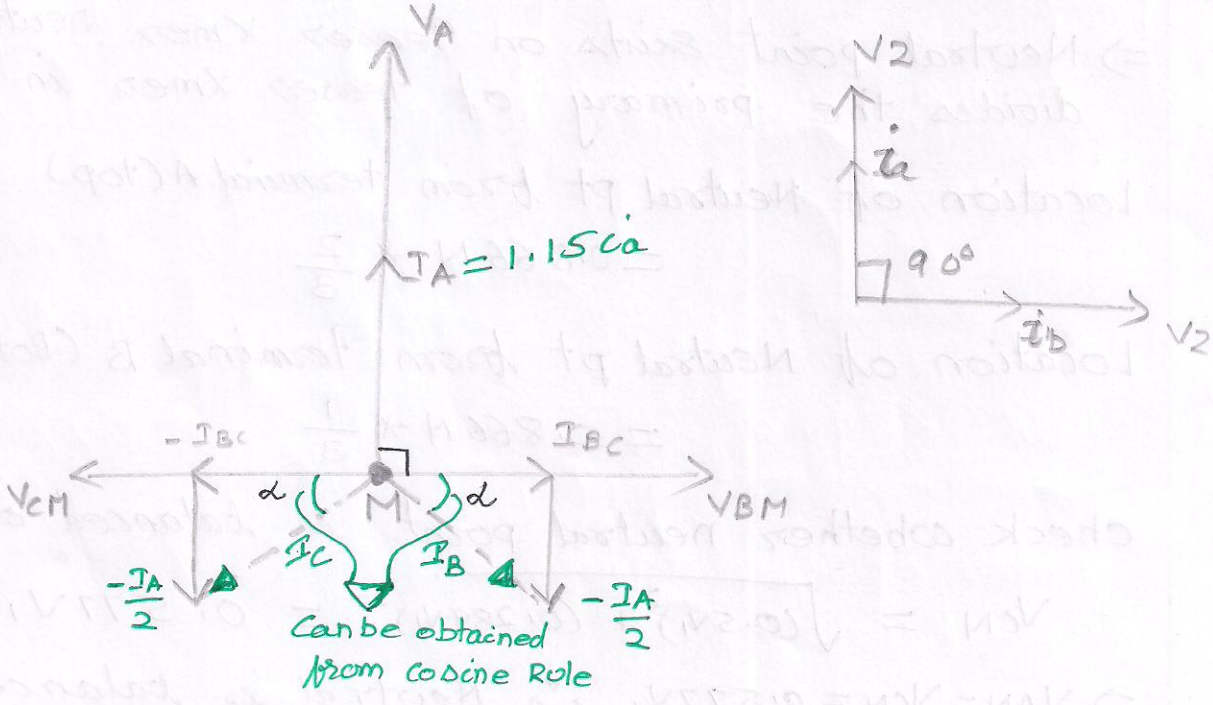
$I_{BC} = i_D$;





$$\bar{I}_B = \bar{I}_{BC} - \frac{\bar{I}_A}{2} \quad ; \quad \bar{I}_C = -\bar{I}_{BC} - \frac{\bar{I}_A}{2}$$

$\bar{I}_A, \bar{I}_B, \bar{I}_C$ are phase currents



Neglect No load current I_o, so primary p.f = Load P.f

→ Check balance in current @ primary of main & teaser xmer?

Let $i_a = 1A$; $i_b = 1A$; & $N_1 : N_2 = 1 : 1$

$\Rightarrow I_A = 1.15\, i_a = 1.15$; $\quad I_{BC} = i_b = 1$

$$I_B = \sqrt{(I_{BC})^2 + \left(\frac{I_A}{2}\right)^2} = \sqrt{1^2 + \left(\frac{1.15}{2}\right)^2} = 1.15A$$

$$I_C = \sqrt{(I_{BC})^2 + \left(\frac{I_A}{2}\right)^2} = \sqrt{1^2 + \left(\frac{1.15}{2}\right)^2} = 1.15A$$

Using Cosine Rule;

$$\left(\frac{I_A}{2}\right)^2 = (I_{BC})^2 + (I_B)^2 - 2 I_B I_{BC} \cos\alpha$$

$$\left(\frac{1.15}{2}\right)^2 = (1)^2 + (1.15)^2 - 2(1.15)(1)\cos\alpha$$

$$1.991875 = 2(1.15)(1)\cos\alpha$$

$$\cos\alpha = 0.866 \Rightarrow \alpha = 30°;$$

$$\cos\alpha = \frac{I_{BC}}{I_B}$$

$$\cos\alpha = \frac{1}{1.15} = 0.866$$

$$\alpha = 30°;$$

$\Rightarrow \bar{I}_A, \bar{I}_B, \bar{I}_C$ are displaced by 120° each

$I_A = 1.15\, i_a = 1.15$; $I_B = 1.15$, $I_C = 1.15$

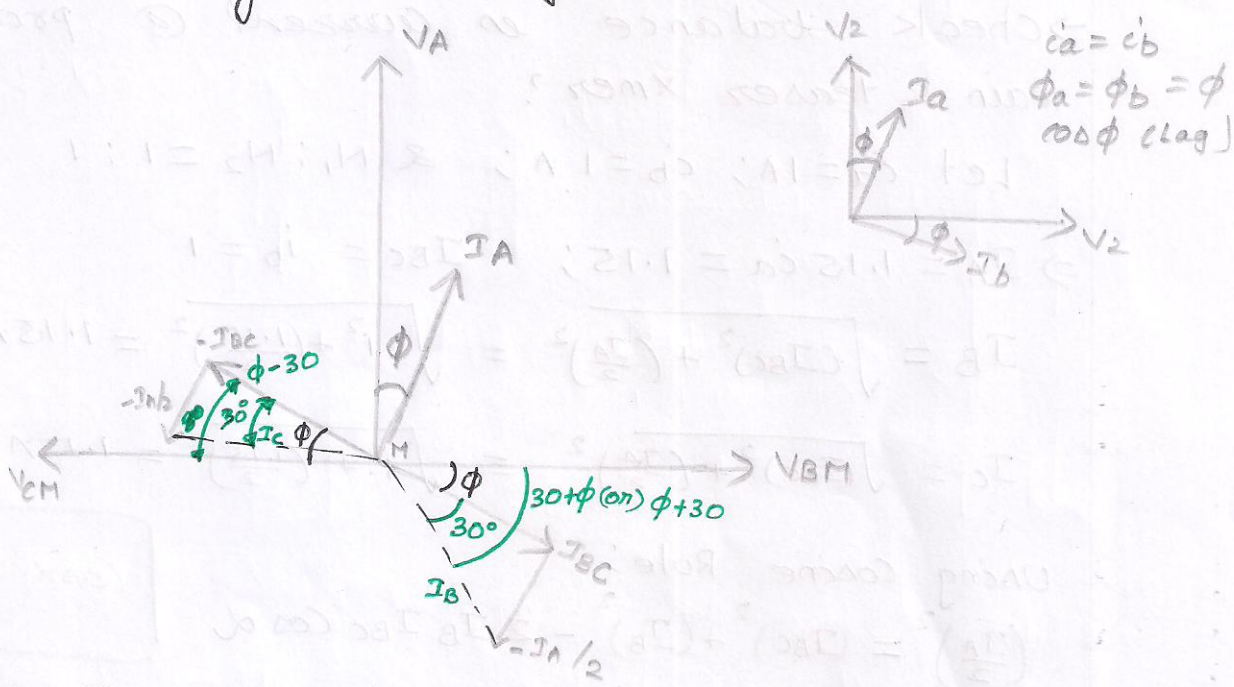
Balanced 3-ph currents exists on primary

Teaser xmer p.f is unity as V_A, I_A are in phase

One half of Main xmer I_B lags V_{BM} by $\alpha = 30°$

other half of Main xmer I_C leads V_{CM} by $\alpha = 30°$

Vector diagram @ Lag p.f



If Teaser Xmer operates at $\cos\phi$

One half of Main Xmer operates @ $\cos(\phi+30)$

other half of Main Xmer operates @ $\cos(\phi-30)$

Load p.f	U Pf	$\cos\phi$ (Lag)	$\phi=30^\circ$ (Lag)	$\phi<30^\circ$ Let $\phi=15^\circ$	$\phi>30^\circ$ Let $\phi=45^\circ$
P.f of Teaser Xmer	U.p.f	$\cos\phi$ (Lag)	$\cos 30$ (Lag)	$\cos 15$ (Lag)	$\cos 45$ Lag
P.f of one half of Main Xmer	$\cos 30$ (Lag)	$\cos(30+\phi)$	$\cos 60$ Lag	$\cos 45^\circ$ Lag	$\cos 75$ Lag
P.f of other Half of Main Xmer	$\cos 30$ (Lead)	$\cos(30-\phi)$	U.p.f	$\cos 15^\circ$ (Lead)	$\cos 15$ Lag

see phasor for clarity

★ Capacity of Scott Connection

$$(KVA)_{scott} = \sqrt{3}\, V_L I_L = \sqrt{3}\, V_1 I_1$$

$$(KVA)_{scott} = \sqrt{3}\,(KVA)_{1-\phi}$$

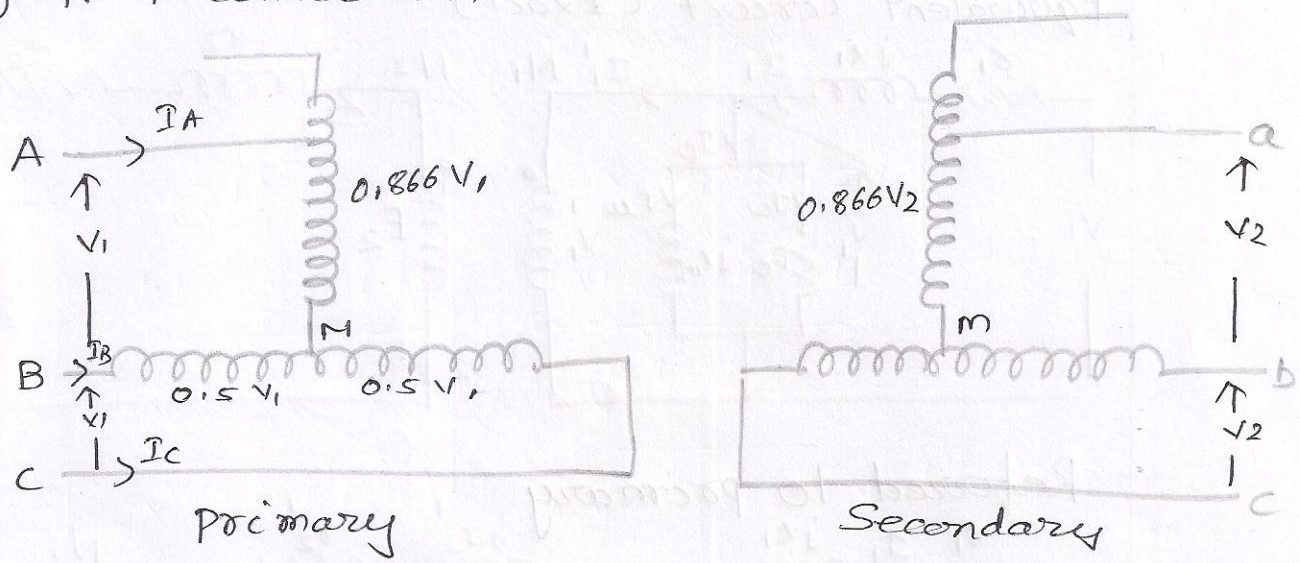
★ Utilization factor $= \dfrac{\sqrt{3}\, V_1 I_1}{V_1 I_1 + 0.866 V_1 I_1} = 0.928$, (Dissimilar Turn's Ratio)

$N_1 : N_2$

$0.866 N_1 : N_2$

For similar turns Ratio (H.T : N_1 : N_2, T.T N_1 : N_2) utilization factor $= \dfrac{\sqrt{3} V_1 I_1}{2 V_1 I_1} = 0.866$ (same as open Δ)

b) T-T Connection



Using two 1-ph xmers, 3-ph supply just like V-V is obtained. Step up / Step Down are possible

KVA Rating of T-T Connection

$(KVA)_{T-T} = \sqrt{3} V_L I_L = \sqrt{3} V_1 I_1$

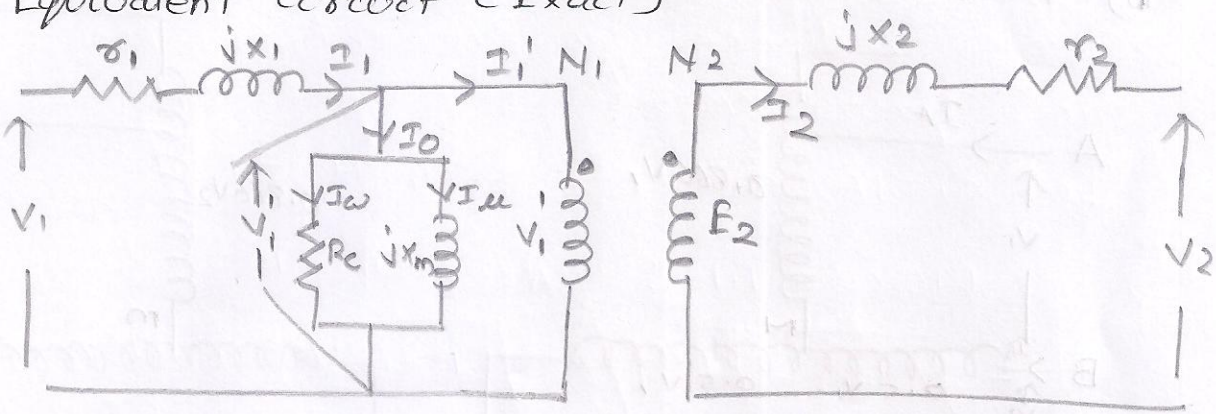
$V_L = V_1$ → Voltage Rating of 1-ph xmer

$I_L = I_1$ → Current Rating of 1-ph xmer

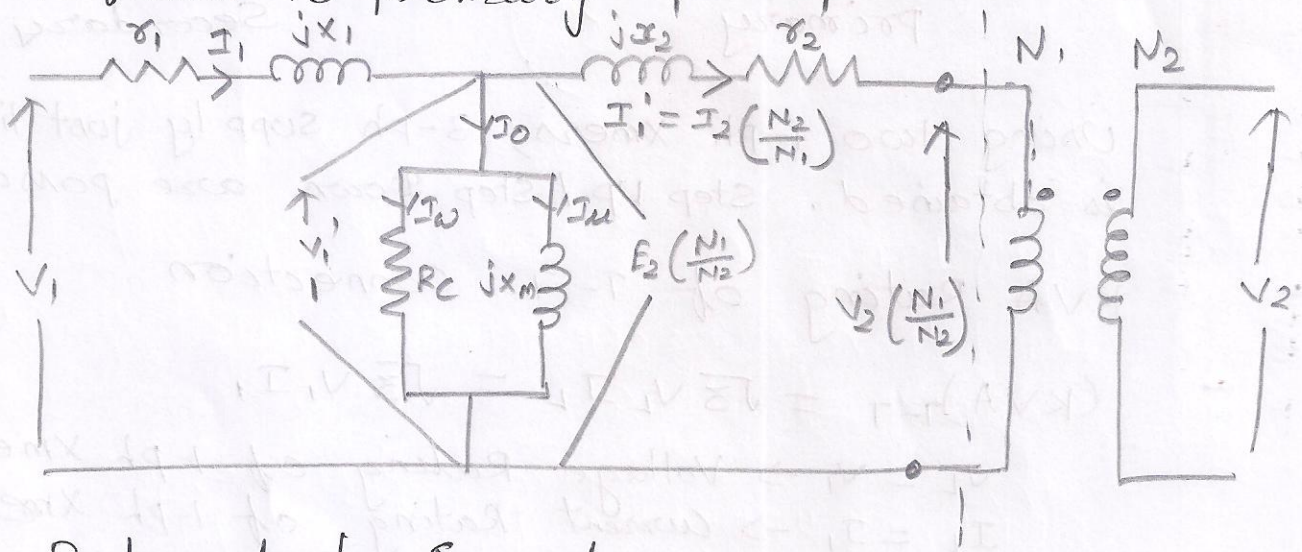
$(KVA)_{T-T} = \sqrt{3}\ (KVA)_{1-\phi}$

Utilization factor $= \dfrac{(KVA)_{T-T}}{\text{Available KVA}} = \dfrac{\sqrt{3} V_1 I_1}{2 V_1 I_1} = 0.866$

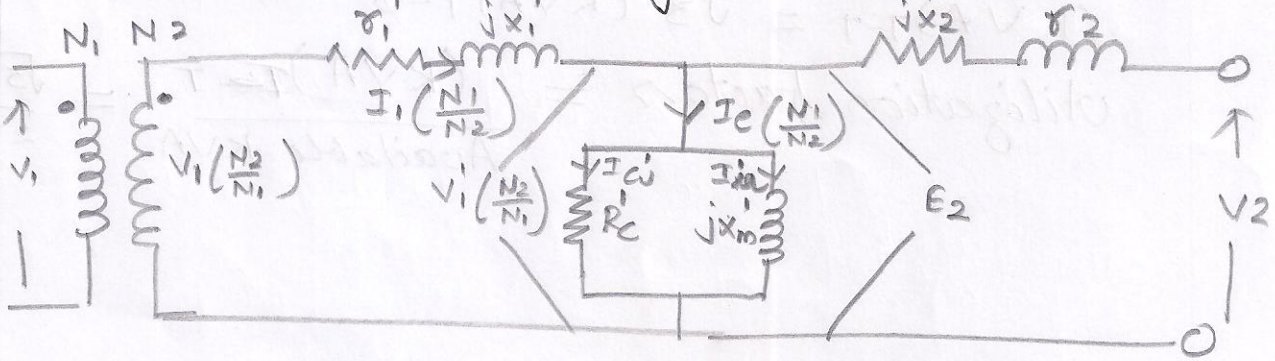
Equivalent Circuit (Exact)



Referred to primary



Referred to Secondary



Referred to Primary

$$\frac{V_1'}{E_2} = \frac{N_1}{N_2} \Rightarrow V_1' = E_2\left(\frac{N_1}{N_2}\right) \quad \Big| \quad \frac{I_1'}{I_2} = \frac{N_2}{N_1} \Rightarrow I_1' = I_2\left(\frac{N_2}{N_1}\right)$$

Referred to Secondary

$$I_2 = I_1'\left(\frac{N_1}{N_2}\right) \; ; \; E_2 = V_1'\left(\frac{N_2}{N_1}\right)$$

$I_2^2 R_{eq} = 3025$

$R_{eq} = 0.825$

$E_2 - V_2 = I_2 R_{eq} \cos\phi + I_2 X_{eq} \sin\phi$

$= (60.6)(0.825)(1) + 0$

$E_2 = 6600; \quad V_2 = 6550;$

→ T1; 1000 KVA; $Z_{1(p.u)} = 0.02 + j0.6$

T2; 500 KVA; $Z_{2(p.u)} = 0.025 + j0.08$

Find largest KVA that can be delivered to this load combination without over loading.

Soln- $Z_{1(pu)} = 0.0632 \angle 71.56$ } on their own bases;

$Z_{2(p.u)} = 0.0838 \angle 72.64$

$Z_{1(p.u)} < Z_{2(p.u)}$

T1 is loaded first

$(KVA)_T = (1000) + \frac{0.0632}{0.0838}(500) = 1377.34$

Loading of Individual machines

Calculate $Z_{(p.u)}$ on common base = 1000 MVA

$Z_{1(p.u)} = 0.0632 \angle 71.565$

$Z_{2(p.u)} = 0.0838 \times 2 \angle 72.64 = 0.16764 \angle 72.64$

$Z_1 + Z_2 = 0.07 + j0.22 = 0.2309 \angle 72.35$

$S_1 = S \frac{Z_2}{Z_1 + Z_2}; \quad S = \frac{1000 * 0.2309}{0.16763} = 1377.4$

$S_2 = S \frac{Z_1}{Z_1 + Z_2} = 1825.3 \text{ KVA};$

→ Three xmers of 400KVA, 11,000/6600; when Operated at rated current with LV winding

Primary voltage = 11 kV

S.C

T1	360V, 3025 ω
T2	400V, 3200 ω
T3	480V, 3250 ω

a) Greatest load at UPF that can be put on these xmers without overloading

$V_{SC1} = 360V$; $V_{SC2} = 400V$; $V_{SC3} = 480V$

$V_{SC} = (I_{SC} Z_{eq})$

$$(KVA)_T = (KVA)_a + (KVA)_b \left(\frac{IZ_a}{IZ_b}\right) + \cdots$$

$(KVA)_a$ → 1st machine full loaded;

(IZ_a) → Impedance Drop at Rated current of xmr a

As Given SC Test performed at Rated current

$V_{SC1} < V_{SC2} < V_{SC3}$

T1 is loaded first ~~then~~

$$(KVA)_T = (400) + \frac{(360)}{(400)}(400) + \frac{(360)}{400}(400)$$

$$= 1060 \text{ KVA};$$

b) Secondary terminal voltage

$$I_{2(Rated)} = \frac{400K}{6.6K} = 60.6A = 1 P.U$$

This flows through T1 as its fully loaded;

$$\%R = \frac{\text{Full load Cu. losses}}{\text{KVA Rating}} = \frac{3025}{400} = 0.756\%$$

$$\Delta V = \%R \cos\phi + \%X \sin\phi = 0.756(1) + \%X(0)$$

@UPF = 0.756%

$$(KVA)_T = (100) + \frac{0.02}{0.03} * (75) + \frac{0.02}{0.025} \times 50$$

$$= 190 \text{ KVA};$$

→ For Normal loading of xmer what should be 1Z1 of each xmer? Assume Z_1 is fixed;

P.U Leakage impedance of machine must be same magnitude on their own KVA Rating

Z_1 is fixed (Given)

$$\boxed{Z_1 = Z_2 = Z_3 = 0.02 \text{ P.U};}$$

~~$S_1 = \frac{1}{Z_{eq}} \quad \frac{1}{2}$~~

Loading on each xmer is obtained by convert them to common base

$$Z_1(p.u) = 0.02 = 2\%$$

$$Z_2(p.u) = \frac{100}{75} \times 0.02 = \frac{8}{3}\%$$

$$Z_3(p.u) = \frac{100}{50} \times 0.02 = 4\%$$

$$\frac{1}{Z_{eq}} = \frac{1}{2} + \frac{1}{8/3} + \frac{1}{4} = \frac{9}{8}$$

$$S_1 = \frac{225}{2\left(\frac{9}{8}\right)} = 100 \text{ KVA};$$

$$S_2 = \frac{225}{\frac{8}{3}\left(\frac{9}{8}\right)} = 75 \text{ KVA};$$

$$S_3 = \frac{225}{4\left(\frac{9}{8}\right)} = 50 \text{ KVA};$$

	KVA	Z(p.u)
Ex T1	100,	0.02
T2	75,	0.03
T3	50,	0.025

$S_{Load} = 225 KVA$

→ While performing Load sharing if Z(p.u) are given they must be transferred to same Base;

Base KVA = 100 KVA

$Z_1(pu) = 0.02$; $Z_2(p.u) = \frac{100}{75} \times 0.03 = 0.04$

$Z_3(pu) = \frac{100}{50} \times 0.025 = 0.05$;

$\frac{1}{Z_{eq}} = \frac{1}{2} + \frac{1}{4} + \frac{1}{5} = \frac{19}{20}$

$S_1 = \frac{S_{load}}{Z_1\left[\frac{1}{Z_{eq}}\right]} = \frac{225}{2 \times \frac{19}{20}} = 118.3 KVA$ Rated (100)

$S_2 = \frac{225}{4 \times \frac{19}{20}} = 59.2 KVA$ (Rated 45)

$S_3 = \frac{225}{5 \times \frac{19}{20}} = 47.4 KVA$; (Rated 50)

$Z_1(pu) < Z_2(p.u) < Z_3(p.u)$

$S_1(p.u) > S_2 > S_3$

↓ overloaded; T1 - overload; T2, T3 underload

→ $(KVT)_T = ?$

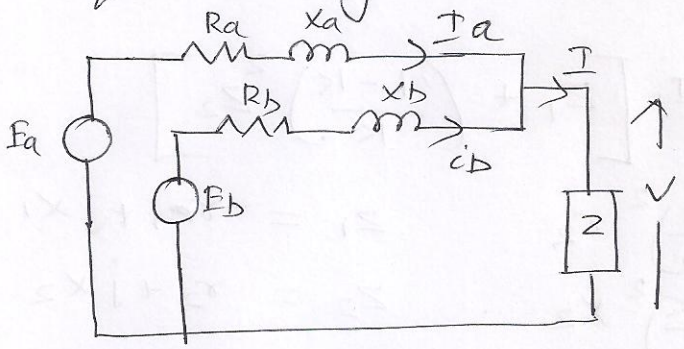
$Z_1(p.u)$ is small 0.02

Here no need to convert to common base

$0.02 < 0.03 < 0.025$

↓ overloaded first

a) Equal Voltage Ratios



$$S_a = S \frac{Z_b}{Z_b + Z_a}$$

$$S_b = S \frac{Z_a}{Z_a + Z_b}$$

c) Unequal voltage Ratios

$$V = E_a - I_a Z_a \Rightarrow E_a - I_a Z_a = E_b - I_b Z_b$$

$$V = E_b - I_b Z_b$$

$$V = I(Z) = (I_a + I_b) Z$$

$$I_c = \frac{E_a - E_b}{Z_a + Z_b + \frac{Z_a Z_b}{Z}}$$

→ Total KVA output without overload on any of xmrs Assuming ~~KVA~~ T1 is Fully loaded among set of xmrs as its $Z_{\%CPU}$ is less compared to others then

$$\text{Total KVA} = (KVA)_1 + \frac{(IZ)_{fl1}}{(IZ)_{fl2}} (KVA)_2 + \frac{(IZ)_{fl1}}{(IZ)_{fl3}} (KVA)_3 + \cdots$$

where $(IZ)_{fl}$ is magnitude of equivalent impedance drops at Rated current of respective xmrs;

→ $$S_k = \frac{\sum_{0}^{n} S_k}{Z_{ekpu} \sum_{1}^{n} \frac{1}{Z_{ekpu}}}$$

Auto Xmer

$$V_1 = \frac{V_2}{K} + I_1\left[Z_1 + \left(\frac{1-K}{K}\right)^2 Z_2\right]$$

$$r_{e1} = r_1 + \left(\frac{1-K}{K}\right)^2 r_2 \qquad Z_1 = r_{e1} + jX_1$$

$$X_{e1} = X_1 + \left(\frac{1-K}{K}\right)^2 X_2 \qquad Z_2 = r_2 + jX_2$$

$$\frac{\text{KVA Rating of Auto Xmer}}{\text{KVA Rating of 2-wdg xmer}} = \frac{1}{1-K};$$

Losses

$$\frac{\text{P.U Full load losses of Auto Xmer}}{\text{P.U Full load losses of 2-wdg xmer}} = (1-K)$$

$$\frac{\text{P.U Impedance Drop of Auto Xmer}}{\text{P.U Impedance Drop of 2-wdg xmer}} = (1-K)$$

$$\frac{\text{Regulation of Auto xmer}}{\text{Regulation of 2-wdg xmer}} = 1-K$$

$$\frac{\text{P.U S.C current of Auto Xmer}}{\text{P.U S.C current of 2-wdg Xmer}} = \frac{1}{1-K}$$

Parallel Operation

No load $\quad I_c = \dfrac{\bar{E}_a - \bar{E}_b}{Z_a + Z_b}$; $\quad \beta = \tan^{-1}\left(\dfrac{X_a + X_b}{R_a + R_b}\right)$

On load

How to draw Phasor's (current) in 3-ϕ Xmers

How to change Xmer connections to facilitate Parallel Operation of Xmer

What is the phase displacement between Primary & Secondary Line voltages for all types of connections

Equivalent ckt diagram referred to 'P' & 'S'.

Refer Text book.